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Liner Materials Exposed to Municipal Solid Waste Leachate

Third Interim Report

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16. ABSTRACT

This report is the third interim report of a project that aims to assess the effects upon various liner materials of extended contact with leachate from simulated sanitary landfills. In this part of the study, the primary exposure tests of liner specimens at the bottom of simulated landfills were supplemented by immersion of 28 different polymeric materials in sanitary landfill leachate. Immersed membranes were tested for changes in physical properties, permeability, and water absorption.

The results of the immersion tests generally confirm the earlier results for membrane liner materials exposed for one year in simulated landfills.

Also reported are results of the water vapor permeability testing of 28 membrane liners, the water absorption of a series of membranes at room temperature and at 70°C, and the retrieval and testing of samples of a 6-year old membrane liner from a demonstration landfill. The monitoring of the simulated landfills during 180 months of operation is described and the analyses of the leachates produced during the period of operation are summarized.

A simple bag test for assessing permeability and physical properties of membrane liners for landfills is described and test results are presented.

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LINER MATERIALS EXPOSED TO MUNICIPAL SOLID WASTE LEACHATE

Third Interim Report

by

Henry E. Haxo, Jr.
Robert S. Haxo
Thomas F. Kellogg
Matrecon, Inc.
Oakland, California 94623

Contract No. 68-03-2134

Project Officer

Robert Landreth
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

Although the information contained herein is preliminary, it will provide a guide and insight to the effects that happen after limited exposure. This information and data could be useful for design purposes if not taken out of context.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This report is the third interim report of a project that aims to assess the effects upon various liner materials of extended contact with leachate from simulated sanitary landfills. In this part of the study, the primary exposure tests of liner specimens at the bottom of simulated landfills were supplemented by immersion of 28 different polymeric materials in sanitary landfill leachate. Immersed membranes were tested for changes in physical properties, permeability, and water absorption. The polymeric materials tested included butyl rubber, chlorinated polyethylene, chlorosulfonated polyethylene, elasticized polyolefin, ethylene propylene rubber, neoprene, polybutylene, polyester elastomer, low-density polyethylene, plasticized polyvinyl chloride, and polyvinyl chloride plus pitch.

The results of the immersion tests generally confirm the earlier results for membrane liner materials exposed for one year in simulated landfills. Specimens of chlorinated polyethylene, chlorosulfonated polyethylene, ethylene propylene rubber, and neoprene liners showed the greatest swell and loss of properties, although specimens of some ethylene propylene rubber and neoprene liners showed low swelling and little loss of properties.

Also reported are results of the water vapor permeability testing of 28 membrane liners, the water absorption of a series of membranes at room temperature and at 70°C, and the retrieval and testing of samples of a 6-year old membrane liner from a demonstration landfill. The monitoring of the simulated landfills during 180 months of operation is described and the analyses of the leachates produced during the period of operation are summarized.

A simple bag test for assessing permeability and physical properties of membrane liners for landfills is described and test results are presented.

This report was submitted in partial fulfillment of Contract 68-03-2134 by Matrecon, Inc., under the sponsorship of The U. S. Environmental Protection Agency. It covers work performed during the period January 1, 1976 to May 31, 1978.

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LIST OF ABBREVIATIONS

cm	-- centimetres
COD	-- chemical oxygen demand
h	-- hour
Hg	-- mercury
ipm	-- inches per minute
MPa	-- megapascals
µmho	-- micro-mho
ml	-- millilitres
mm	-- millimetres
pH	-- hydrogen ion concentration
ppi	-- pounds per inch
ppm	-- parts per million
psi	-- pounds per square inch
TVA	-- total volatile acids

METRIC CONVERSION TABLE

FACTORS FOR CONVERTING DATA IN U. S. CUSTOMARY UNITS TO SI METRIC UNITS

Inches to centimetres (cm)	x 2.54
Feet to metres	x 0.3048
Mils to centimetres (cm)	$x\ 2.54 \times 10^{-3}$
Mils to millimetres (mm)	$x\ 2.54 \times 10^{-2}$
Pounds per square inch (psi) to megapascals (MPa)	$x\ 6.895 \times 10^{-3}$
Pounds per inch (ppi) to kilo Newtons per metre (kN/m)	$x\ 1.751 \times 10^{-1}$
Pound (force) to Newtons	x 4.448

Some U. S. Customary units are used in this report as they are commercially used in the United States in the solid wastes industry as well as the liner production and installation industries.

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SECTION I

INTRODUCTION

The lining of sanitary landfills with impervious materials has been found to be a feasible method of intercepting and controlling leachate that may be generated in a landfill and preventing it from entering and polluting surface and ground waters. A wide variety of materials were potentially useful for lining sanitary landfills but this application and information regarding the effects of leachate contact were almost nonexistent when this study was initiated. A technology that had been developed to impound and control water in canals, ponds, etc., appeared to be applicable to the lining of sanitary landfills, but the effects of prolonged contact of liner materials with leachate were not known. The development of this type of information was needed to insure the choice of adequate materials for lining sanitary landfills. This study was undertaken to develop such information in terms that could be readily understood by engineers, designers, and users.

OBJECTIVES

The primary objectives of the project as a whole are as follows:

1. To determine the effects of exposure to leachate from compacted, municipal refuse on the physical properties of 12 selected liner materials (excluding soils and clays) that were believed to be potentially useful for the lining of sanitary landfills.

2. To determine the durability of these liner materials and to estimate their effective lives when exposed to leachate for prolonged periods under conditions comparable to those encountered in a sanitary landfill.

3. To develop accelerated testing procedures for evaluating new materials that may have potential application to lining landfills.

4. To analyze the costs of sanitary landfill liner materials, including installation costs and the benefits of greater durability.

BACKGROUND

The primary effort in this project has been to assess the effects of landfill leachate on a wide range of potential liner materials (except soils and clays) under conditions that simulate real-life exposure. In taking this approach, which would develop information that would be directly translatable

into use in field application, we constructed 24 simulated landfills, each containing about one cubic yard of shredded municipal refuse. Specimens, two ft in diameter, of 12 different lining materials, six polymeric membranes and six admixes, were sealed in the bases (1-4). Leachate was produced in each generator by saturating the refuse and adding one in. of tap water on a biweekly basis to equal 26 in. of water per year. Leachate was allowed to pond on the liner specimens to a depth of one ft to supply an hydraulic head and thus a driving force for the leachate to seep through the liner specimen.

The exposure tests of the primary membrane liners were supplemented by simultaneously exposing two sets of small specimens of 42 polymeric membrane materials. These were buried in the sand above the primary liners.

The permeabilities of the primary liners are being assessed by measuring the amount of leachate that seeps through the liners. The effects of leachate upon the properties of liners are determined by recovering and testing the liner specimens at two time intervals, initially planned for 12 and 14 months, but now planned for 12 and 55 months.

In November 1975, after a year of exposure, the first of the two sets of samples was recovered, and properties of the leachate exposed materials were measured. Results were presented in the Second Interim Report (2). One year of exposure to landfill leachate had only relatively minor effects upon all the liner materials under test. All materials appeared to have maintained their original permeabilities. The admix materials became somewhat more impermeable.

Losses were measured in the compressive strength of the admix materials and in the physical properties of some of the polymeric membranes. Most membranes swelled; the chlorinated polyethylene and the chlorosulfonated polyethylene were affected the most, and the polyolefins, polyethylene, polypropylene, and polybutylene, the least.

The limited effects of the one year of exposure on the liner materials, even in leachate that was considered to be relatively concentrated, made long-term extrapolations to liner service life very tenuous. Consequently, the exposure period was extended and the dismantling and testing of the liner materials was postponed, first to June 1978, and later to July 1979. In addition, the scope of the project was expanded to include immersion studies, analyses of liner materials, additional permeability studies, and efforts to develop simpler testing procedures for evaluating liner materials for sanitary landfills.

Progress in this project is being presented in a series of interim reports. The First Interim Report (1) describes the overall technical approach, the construction of the leachate generators, the selection of liner materials, the loading of the cells with ground refuse, and the bringing of the cells to field capacity. In that report, various liner materials are discussed, and the bases for selecting the 12 primary materials are presented. The original properties of unexposed liner materials were determined so that the effects of the various exposures could be measured

from these values. Cost data for the various materials used to line ponds, lagoons, pits, etc., are also examined.

The Second Interim Report (2) presents the results of exposing liner materials to leachate for one year. The monitoring of the generators is described, and the analyses of leachate generated over the one-year period are reported. Also described are the overall operation of the leachate generators and the performance of the materials employed in fabricating the apparatus used in this project. Permeability of the various materials to water and leachate is discussed. The report also includes Appendixes of test data taken from the First Interim Report (1).

This report, the Third Interim Report, covers the period January 1976 through May 1978, and concentrates on the membrane liner materials. Discussed are the testing of liner materials by immersion in leachate; water vapor permeability, leachate, and water absorption of polymeric membranes; permeability of thermoplastic, heat-sealable membranes to leachate by osmosis; the continued monitoring of the leachate generators, and the recovery and testing of a sample of polyvinyl chloride liner taken from a demonstration landfill. The design, construction, and operation of the immersion system are also described.

SECTION 2

SUMMARY

IMMERSION TESTS

Three sets of 28 different polymeric membrane liner specimens were immersed in a series of tanks containing a blend of leachates produced in the 12 generators. This system was designed to maintain anaerobic conditions and to allow the leachate to flow slowly through the tanks. After 8 months of immersion, one set of the 28 lining specimens was removed and tested.

The eight months of immersion in leachate appears to be approximately equivalent to one year of one-sided exposure of the primary specimens of the same materials in the bases of the generators. This immersion condition duplicated the effects on the buried specimens of the same liners placed in the sand. In the case of the other lining materials which are not being exposed in the generators, the effects were not large. The liners based upon chlorinated polyethylene, chlorosulfonated polyethylene, and neoprene tended to swell and soften more than the other lining materials. On the other hand, the polyolefins, such as polyethylene, polybutylene, elasticized polyolefin, and polyester elastomer, all of which are partially crystalline, swelled and softened the least. The polyvinyl chloride membranes approximated the latter materials in swelling and changes of properties.

WATER VAPOR PERMEABILITY

Permeability testing of the various membrane liner materials has been continued, using several test methods. Results of water vapor permeability, by ASTM E-96, Method BW (5), are reported for 27 different liner materials, including butyl rubber, chlorinated polyethylene, chlorosulfonated polyethylene, elasticized polyolefin, ethylene propylene rubber, neoprene, polyester, and polyvinyl chloride. As a group, the polyvinyl chloride liner materials have the highest permeability to water vapor and the butyl rubber and elasticized polyolefin the lowest. Permeability appears to increase with test time, probably because of swelling of the membranes by water.

OSMOTIC BAG TEST

A laboratory test method now being developed appears feasible for assessing membrane materials for lining sanitary landfills and the containment of hazardous wastes. In this test, leachate or other waste fluid is sealed in a small bag fabricated of the material under test. The bag is then placed in a somewhat larger bag containing deionized water. The

permeability of the membrane is assessed by measuring weight increase of the inner bag and pH and conductivity of the deionized water. After the permeability test is completed, the physical properties of the bag material can be measured to determine the effects of exposure to the leachate. Data are presented for bags made of six different polymeric membranes in which leachate and 5% salt solution were sealed. During immersion in the deionized water, the bags increased in weight and the deionized water changed in pH and conductivity, depending on the membrane.

WATER ABSORPTION TESTS OF SELECTED MEMBRANE LINERS

Two series of water swelling tests, run for 100 weeks at room temperature and at 70°C, indicate that membrane liners of neoprene, chlorosulfonated polyethylene, and chlorinated polyethylene continually swell in water, whereas the polyethylene, polybutylene, polyester, and elasticized polyolefin reach a plateau in the swell, as does polyvinyl chloride. At least one of the polyvinyl chloride liners tended to harden on long-term exposure, indicating loss of plasticizer.

MONITORING OF THE LEACHATE GENERATORS

The 12 simulated landfills in which 12 different liner materials are being exposed to leachate continue to be operated. No leachate has been collected below the liners of seven of these generators after 43 months of operation. Two of the generators with butyl rubber and polyethylene membrane liners appear to have failed at the epoxy resin seals between the liners and the bases of the generators. Two admix liners, soil asphalt and soil cement, have allowed minor amounts of leachate to seep into the bases. The current schedule calls for the operation of the 12 generators to be continued until July 1979, when they will be disassembled and the liners will be retrieved and tested.

The leachate that is being produced in the 12 generators is gradually becoming more dilute in solids content, chemical oxygen demand, and volatile acids. Also, the average pH has now risen from approximately 5 to 6.5, with leachate from several generators over 7.0.

The refuse in the cells continues to consolidate linearly with time. After 43 months, the average consolidation of shredded refuse in the 12 remaining generators is 16%.

RECOVERY AND TESTING OF MEMBRANE LINER FROM A LANDFILL

Samples of a polyvinyl chloride liner were retrieved from a demonstration landfill and tested. This liner had good properties and probably changed little during the six-year exposure period. Because of an impermeable clay cover on the membrane, leachate probably did not directly contact the liner; furthermore, the leachate appeared to be quite dilute. There were no data available on the properties of the liner before exposure with which to make a comparison.

SECTION 3

FUTURE WORK

The period covered by this project has been extended through November 1979, during which time the following tasks will be performed:

- Exposure of the primary liners in the bases of the leachate generators will be continued through June 1979, when they will have been exposed for 56 months. The exposure of the small supplemental specimens buried in the sand above the primary liners will also be continued.

- The immersion and osmosis bag tests now underway will be continued.

- The second set of 28 specimens will be recovered in June 1978 and tested after 19 months of immersion in leachate and the third and final set will be removed and tested in June 1979 after 30 months of immersion in leachate. At the end of the project the membrane osmosis bags will be cut and the membranes tested.

- The small specimens buried in the sand above the primary liners in the two leachate generators containing the asphaltic membranes will be recovered and tested in June 1978 to assess the effects of 43 months of exposure to leachate. These two primary liners will be inspected and one will be sampled and a repair made. New small membrane samples will be placed in the sand and the generators will be returned to operation for the remainder of the project.

- Permeability studies will be expanded as follows:

  a. Additional bags will be prepared to assess the permeability of membrane liner materials to water and to dissolved constituents of the leachate.

  b. A newly-designed top-pressure permeameter will be used to determine the permeability of membrane liners to leachate.

  c. Additional tests will be made of water vapor permeability using ASTM E-96, Method BW.

  d. The permeability of membrane liners to gases, such as methane, carbon dioxide, and air, will be determined.

- The various methods of joining dissimiliar lining materials will be investigated and, if necessary, experimental work will be performed to develop adequate methods for limited combinations.

- The analysis of membrane liners will be completed for possible use in specifications.

- The specifications now being followed by manufacturers, suppliers, and installers of various liner materials will be reviewed.

- An investigation of soil-membrane liner composites will be carried out to determine the effect of a soil cover on the rate of deterioration of the membrane liner.

SECTION 4

EXPERIMENTAL WORK

IMMERSION OF MEMBRANE LINERS IN LEACHATE

Assessing liner materials for lining sanitary landfills by exposing to leachate at the bottom of simulated landfills, such as is being done in this project, is time-consuming and expensive. Simpler methods are needed to evaluate a liner material for this application. The results obtained in this project should form a basis for the development of simpler procedures which will correlate with the results obtained and with actual landfill experience.

An obvious simplification of the simulated landfill method is to immerse specimens of various liner materials in the leachate from municipal refuse and determine the changes in properties during the exposure. The availability of leachate from the simultated landfills presents the opportunity for obtaining a direct correlation between these two procedures for use in developing a laboratory evaluation test. The same materials can be tested by the two methods in essentially the same leachate.

Membrane liners are amenable to immersion testing but admix materials pose many experimental problems in such types of tests. The study which was undertaken of the effects of immersion in leachate was, therefore, restricted to membrane liners.

Our basic plan was to immerse liner specimens of sufficient size to be able to obtain data on volume and area swell and on the same physical properties as were measured on the primary liners. The leachate from the generators would be used and allowed to flow slowly past the specimens. The liner materials selected would include some of the materials being exposed in the simulated landfills as well as new materials which have subsequently become available either commercially or on a developmental basis. In order to obtain sufficient data with which to make projections of service life, it was planned to immerse three sets of liner specimens and to withdraw them at three time intervals. Originally it was planned to immerse the specimens for six months, 12 months and 18 months, but the times were later changed to eight months, 19 months and 30 months.

Design and Construction of the Immersion System

We originally planned to attach small cells or bags containing the liner specimens directly to the individual leachate generators and allow the leachate to flow by the specimens as it was continuously being collected. Such a design would maintain the anaerobic condition that existed in the generator where the primary liners were being exposed. However, the leachates being produced were varying in composition from one generator to another which would make comparison between liners difficult. Furthermore, the number of containers would be large and monitoring of the 12 generators with the attached containers posed a variety of problems and additional effort.

This design was replaced with one in which blended leachate from the 12 generators slowly flowed through a series of polyethylene tanks in which the membrane specimens could be hung. We felt this arrangement would be acceptable because only small changes in composition of the leachate were observed when it was stored in polyethylene containers at room temperature over a period of one month. Furthermore, this design allowed easy exposure of more specimens, exposures of all specimens to the same leachate, and required considerably less time to construct and monitor.

After considering a wide variety of containers for use as immersion cells, we selected heavy-duty high-density polyethylene tanks (Nalgene), 14 x 10 x 10 in. in dimensions, each with a 6-gal capacity. These tanks, which were placed on a 3.5 ft wooden platform, are of heavy-gauge construction with flat lids from which the specimens were hung on stainless steel hooks. Inlets and outlets were installed, and the lids with the specimens were welded to the tanks (Figure 1). The flow of the leachate through the tanks was by gravity feed from a drum containing leachate placed above the tanks as shown in Figure 2. Problems were encountered with this arrangement due to plugging of the system by precipitation of solids in the leachate.

A Masterflex pump was, therefore, installed that delivered leachate at the rate of 14 ml per minute through the tanks, recirculating the supply of leachate in about 12 days (Figure 3).

Exposure Specimens

Twenty-eight different membranes of 11 different polymeric materials were selected for immersion testing:

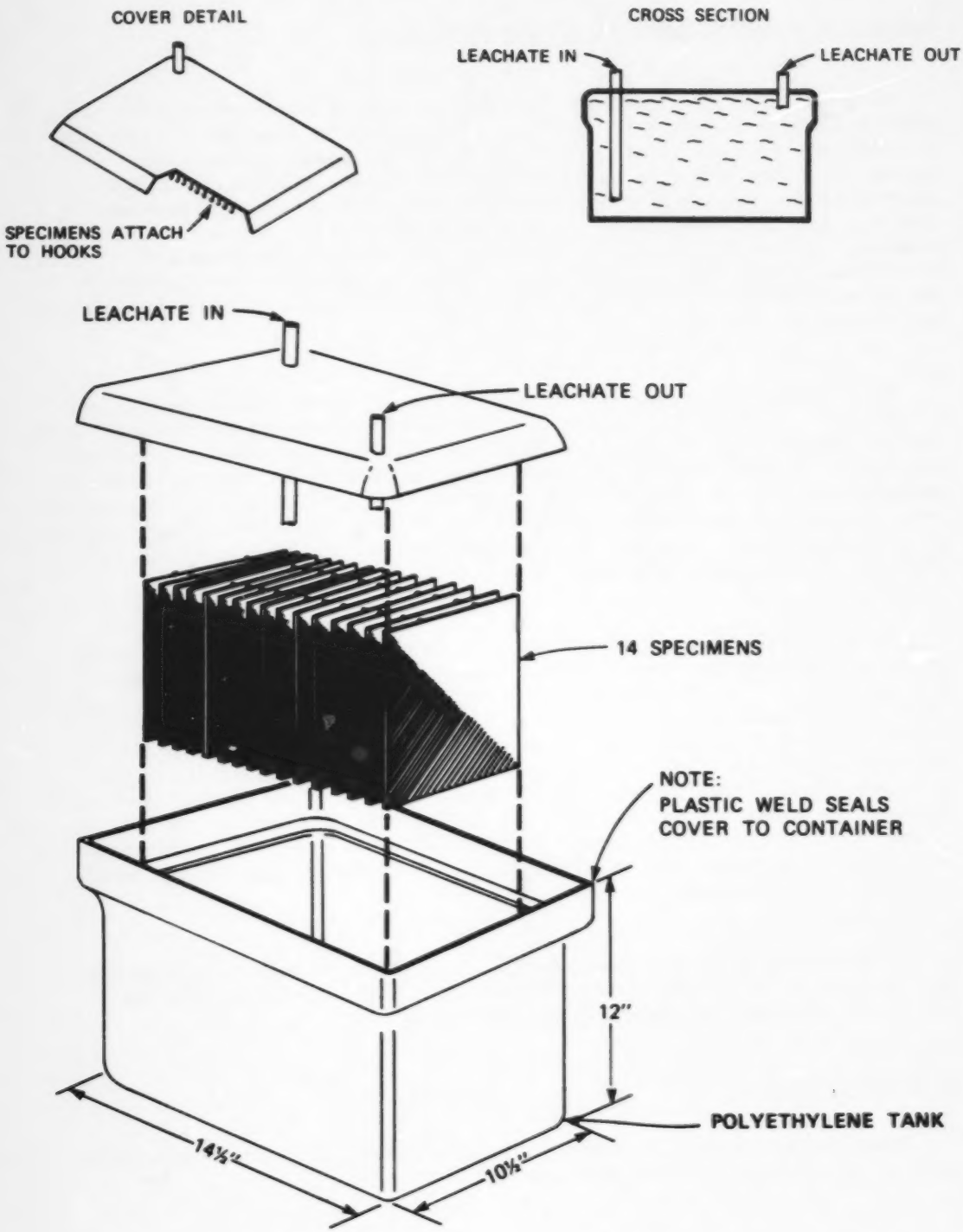

Figure 1. Individual polyethylene immersion tank, showing method of holding specimens and the inlet and outlet for the leachate.

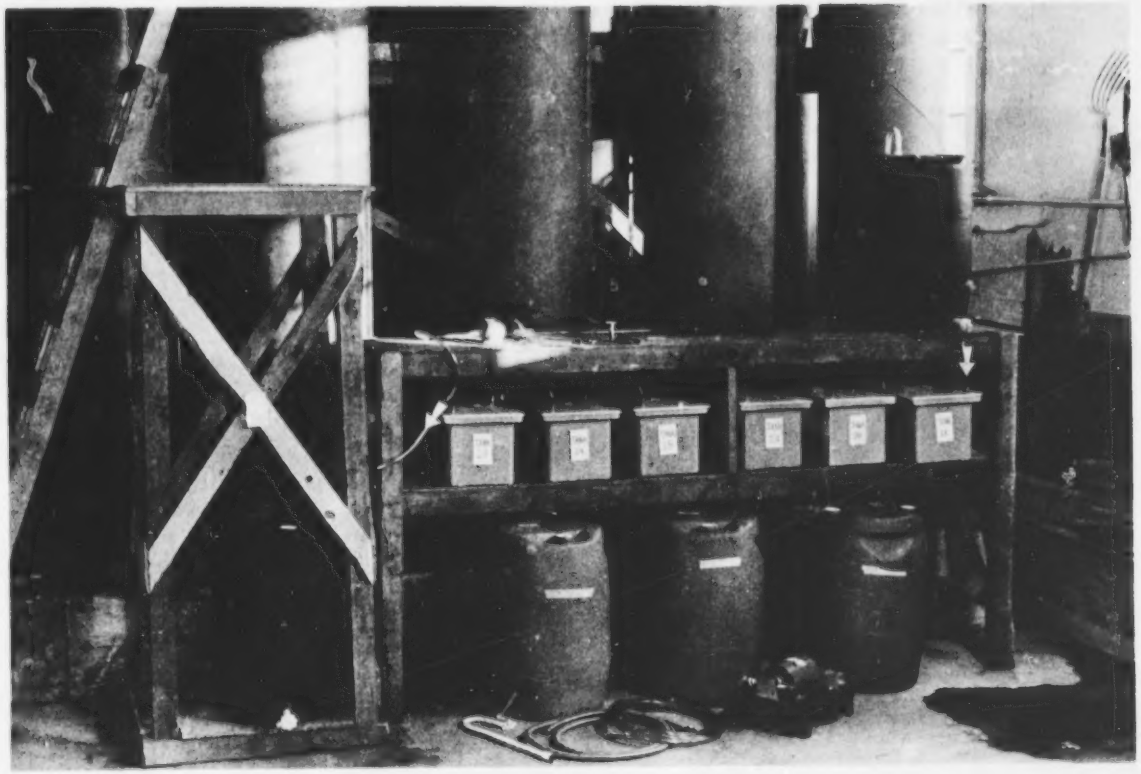

Figure 2. Immersion system set up with gravity feed of leachates through the tanks. Leachate generators are in the rear.

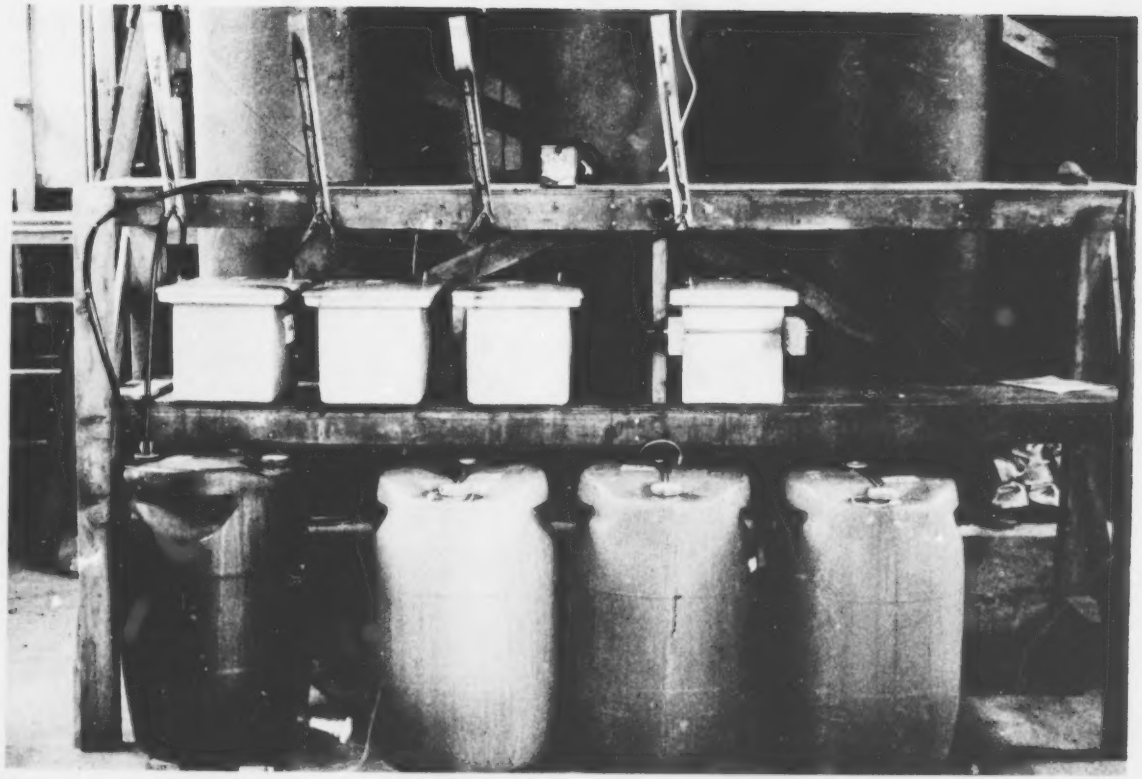

Figure 3. Immersion system set up with pump and gas relief valves on individual tanks. The pump is in the center of the upper shelf; leachate generators are in the rear.

Type of Material	Number of different liners immersed
Butyl rubber	1
Chlorinated polyethylene (CPE)	3
Chlorosulfonated polyethylene (CSPE)	3
Elasticized polyolefin	1
Ethylene propylene rubber	5
Neoprene	4
Polybutylene (PB)	1
Polyester elastomer	1
Polyethylene (PE)	1
Polyvinyl chloride (PVC)	7
PVC and pitch	1
Total	28

Three specimens of each membrane were immersed in the leachate in sets of the 28 so that they could be removed from the system after three exposure periods.

The 8 x 10 in. size of the test specimens was sufficient to make all of the tests required. The specimens were hung vertically 0.92 in. apart in the tanks (Figure 1).

The tests which were performed on the lining materials before exposure and at three subsequent intervals are:

Weight, before and after exposure.
Dimensions, before and after exposure.
Tensile strength, in machine and transverse direction, ASTM D412.
Hardness, ASTM D2240.
Tear strength in machine and in transverse direction, ASTM D264, Die C.
Puncture resistance, FTM 101B, Method 2065.
Volatiles at 105°C, ASTM D297.
Specific gravity, ASTM D297.

The physical properties of the unexposed lining materials that were immersed are presented in Appendix A.

Operation of Immersion System

Approximately 48 gallons of leachate obtained by blending the output of the 12 generators, was introduced into the system every 4 weeks and a similar amount of the used leachate was drawn off. The new leachate was the accumulation of the two previous collections of 24 gallons each from the generators. Samples of both the new and used leachate were tested at each addition for: pH, chemical oxygen demand (COD), total solids (TS), total volatile solids (TVS), and total volatile acids (TVA).

The differences in the composition of the leachate added and of that removed were small, indicating the air-tight, anaerobic character of the system. During the initial operation of the system, the analytical results (Table 1) were close to the calculated averages of the leachates from the generators (see below, "Monitoring the Leachate Generators"). In later months, however, differences developed between the two that may have been caused by biological contamination of the blended leachate. The pH of the leachate from the generators (Figure 4) is increasing at a regular rate (see below, "Monitoring the Leachate Generators"); however, the pH of the blended leachates in the system became substantially higher in October-November 1977 and has remained high.

TABLE 1. ANALYSIS OF LEACHATE USED IN THE IMMERSION SYSTEM[a]

Property	Leachate added to system	Leachate removed from system
pH	5.27	5.27
Chemical oxygen demand, g/l	32.6	29.0
Total volatile acids, g/l	11.3	11.3
Total solids, %	1.70	1.80
Total volatile solids, %	0.94	1.00

[a]Samples were taken on January 31, 1977.

Some gas was generated in the tanks, which necessitated the addition of relief valves to prevent pressure buildup. During the course of the operation there were two leaks in the welds that required repairs.

Results of Exposure to Leachate

After eight months of immersion, two tanks containing one set of test specimens were removed from the system and the exposed specimens were recovered and tested to assess the effects of exposure to leachate. Retrieval consisted of bypassing the cells to be removed, disconnecting them, flushing them with water, and then cutting open the cells. Exposed liner samples were stored in polyethylene bags to retain moisture until testing could be completed. The results of analyses and measurements of physical properties of the exposed specimens are presented in Appendix B.

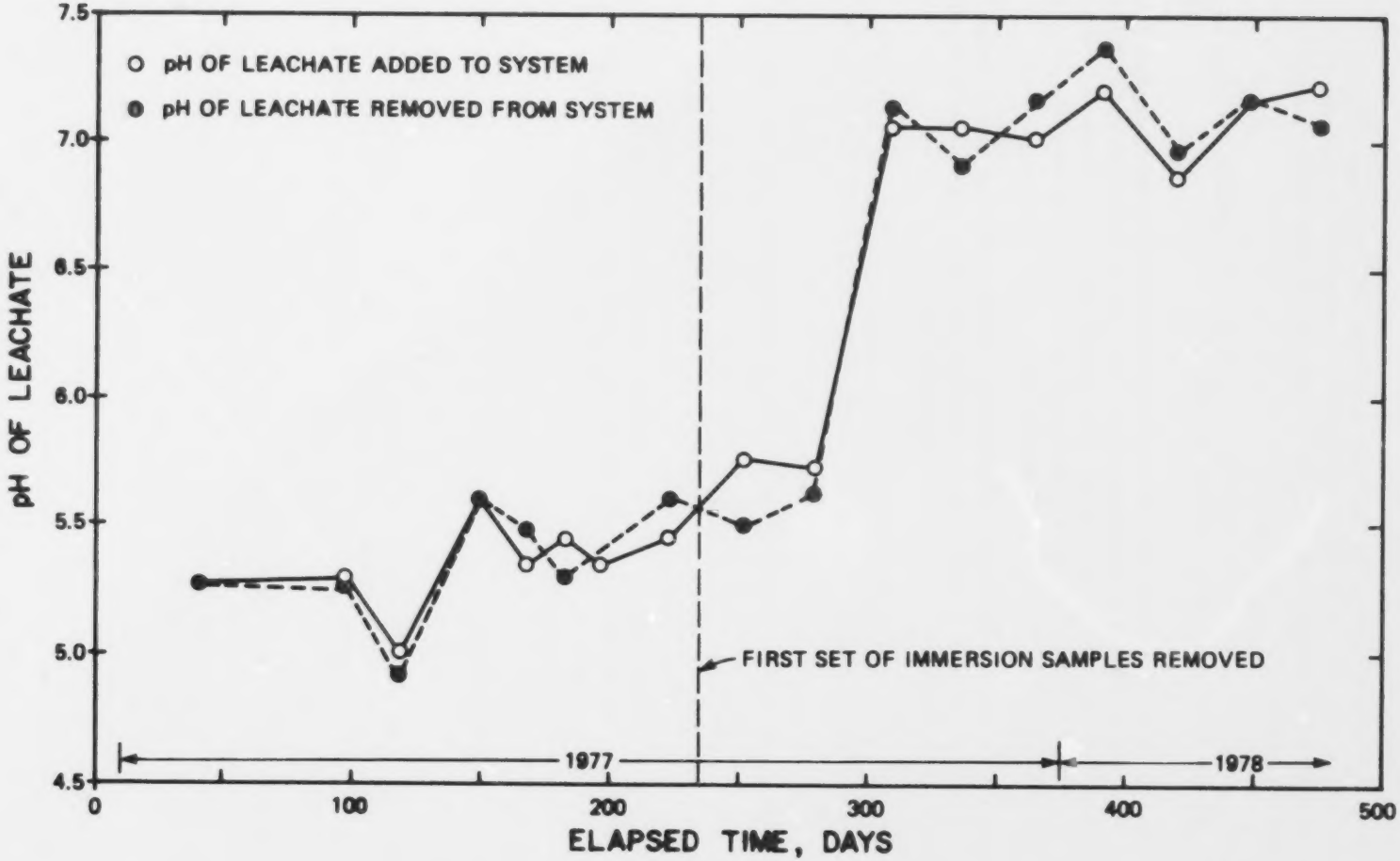

Figure 4. Leachate pH during the immersion test.

Table 2, based upon selected data from Appendixes A and B, summarizes the effects of eight months of immersion of the 28 liner materials in leachate, compares the 11 different types of material, and shows the ranges of leachate absorption and the retention of physical properties for each type of material.

The materials tested fell into three groups with regard to swelling or leachate absorption during the eight months:

1. Those with the greatest leachate absorption, which included the chlorosulfonated polyethylene and the chlorinated polyethylene liners (13% to 19% and 8% to 10%, respectively). Neoprene and ethylene propylene rubber ranged from low to high absorption (1% to 19% and 1% to 13.5%, respectively).

2. Those with low leachate absorption, which included the polyolefins, plasticized polyolefin, and polybutylene (all with 0.1% absorption), and polyethylene (with 0.6% absorption).

3. Those with relatively low leachate absorption, which included polyvinyl chloride (1% to 3%), polyester (2%), and butyl rubber (1% to 2%).

The membrane liner of polyvinyl chloride plus pitch swelled 6%.

Changes in physical properties generally followed swelling. Those specimens that swelled little changed relatively little in physical properties. The materials that exhibited significant drops in tensile strength during the exposure period were neoprene, chlorinated polyethylene, and chlorosulfonated polyethylene. They were the materials that swelled the most. The polyolefins showed little loss, as did the polyvinyl chloride liners. In elongation at break, there was a similar effect, except that one of the ethylene propylene rubber materials exhibited a significant loss when tested in the transverse direction. This material appeared to have cured or crystallized during exposure, resulting in a substantial increase in modulus.

A general decrease in hardness and modulus of the liners occurred during exposure, but there were some increases, i.e., the ethylene propylene rubber discussed above and some specimens of chlorinated polyethylene and chlorosulfonated polyethylene.

Overall, the polyolefins and polyvinyl chloride materials changed the least during the immersion period. As groups of materials, the polyvinyl chloride membranes varied the least during this time period and neoprene and ethylene propylene rubber varied the most.

TABLE 2. SUMMARY OF THE EFFECTS OF IMMERSION OF POLYMERIC MEMBRANE LINERS IN LEACHATE FOR 8 MONTHS

Polymer	No. of liners in test	Absorption of leachate, %	% Original value for unexposed membrane			Change in hardness, points
			Tensile strength	Elongation	S-200	
Butyl rubber	1	1-2	90-97	104-106	85-86	0
Chlorinated polyethylene	3	8-10	80-115	64-135	84-123	-5 to -1
Chlorosulfonated polyethylene	3	13-19	82-124	97-107	47-113	-20 to -4
Elasticized polyolefin	1	0.1	86-94	91-92	102-106	0
Ethylene propylene rubber	5	1-13.5	90-91	76-138	98-220	-1 to +2
Neoprene	4	1-19	69-100[a]	82-103[a]	79-102[a]	-11 to +5
Polybutylene	1	0.1	96-99	96-97	99-103	-3
Polyester elastomer	1	2.0	99-115	101-108	95-110	-4
Polyethylene	1	0.6	110-180	96-181	100-116	-7
Polyvinyl chloride	7	1-3	91-110	98-129	76-102	-2 to +1
Polyvinyl chloride + pitch	1	6.0	92	109-133	93-108[b]	-2

[a]Data on fabric-reinforced neoprene liner #42 were not included.
[b]S-100 - unexposed specimen broke at 150% elongation.

As indicated above, there were considerable variations among the specimens of a given polymer type, as shown in Table 2 and Appendix B. These variations within a single polymer group point out the importance of other factors in addition to the polymer that determine the properties of a given liner composition. For example, swelling would be greatly affected by crosslinking, percent of crystallinity, and the type and amount of fillers used. Minor amounts of other constituents, such as soaps and occluded salts from the preparation of the polymer can also affect swell.

Two additional sets of the same 28 polymeric liner materials remain in the immersion tanks. These will be retrieved and tested after immersion periods of 19 and 30 months.

WATER VAPOR PERMEABILITY OF POLYMERIC MEMBRANE LINING MATERIALS

The very low permeabilities of polymer membrane liners, compared with those of soils and admix liner materials, have made it difficult to obtain compatible permeability data for all these materials. Polymeric membrane liners are nonporous. Therefore, the rate of transmission of a liquid, such as water, depends upon its solubility in the liner and the rate of diffusion of the molecules of the liquid through the liner. Permeameters normally used for soils are not applicable for measuring the permeability of membranes. Consequently, the polymeric membrane liner industry has been using water vapor transmission as a measure of the permeability of polymeric liners. This type of test was used to determine the permeability of the six polymeric membranes that are being exposed as the primary liners sealed in the bottoms of the leachate generators (2).

Test Method

The test method used in our initial measurements basically followed ASTM E-96, "Water Vapor Transmission of Materials in Sheet Form," Method BW (5). In this test a small water cup with a membrane specimen cover is inverted to wet the specimen (Figure 5). The cup in the inverted position is placed in a box having controlled temperature, humidity, and air stream, and its loss in weight is observed as a function of time. This test is intended for those applications in which one side is wetted under conditions where the hydraulic head is relatively unimportant and the moisture transfer is governed by capillary and water vapor diffusion forces. The driving force is supplied by the difference in the vapor pressure on the two sides of the membrane.

The conditions under which these tests were initially performed were at variance with those specified in the ASTM Test Method E-96, leading to high absolute values of vapor transmission. In particular, the relative humidity on the outside of the cups was significantly less than 50% and the air velocity was substantially higher than that called for in the method. The relative values, however, are valid (Table 3).

Figure 5. E96 water vapor permeability cup and auxiliary equipment.

TABLE 3. EFFECTS OF TEST CONDITIONS ON WATER VAPOR PERMEABILITY OF POLYMERIC MEMBRANE LINERS

Polymer	Liner No.	Thickness mils	Thickness cm	Rate of water vapor transmission, g/d·m² Test conditions ASTM[a]	Rate of water vapor transmission, g/d·m² Test conditions Ref. 2[b]	Water vapor permeance, 10^{-2} g/d·m²·mmHg (metric perm) Test conditions ASTM[a]	Water vapor permeance, 10^{-2} g/d·m²·mmHg (metric perm) Test conditions Ref. 2[b]	Water vapor permeability, 10^{-3} g/d·m²·mmHg·cm (metric perm-cm) Test conditions ASTM[a]	Water vapor permeability, 10^{-3} g/d·m²·mmHg·cm (metric perm-cm) Test conditions Ref. 2[b]
Chlorinated polyethylene	12	33.3	0.085	0.264	0.610	2.10	4.60	1.76	3.70
Chlorosulfonated polyethylene	6	37.0	0.094	0.422	0.825	4.21	6.20	3.79	5.70
Polyvinyl chloride	17	20.0	0.051	2.97	3.69	24.4	27.7	12.0	15.0

[a] Results of tests made under conditions specified in ASTM E96 (data from Table 4).
[b] Results of tests made in low relative humidity and high air flow (data from Ref. 2).

To comply with the test conditions of the ASTM method, we constructed a small cabinet (Figure 6), to hold the cups. The cabinet has a built-in controlled air flow and is operated in a constant-temperature and humidity room controlled at 72 $\pm$ 1°C and 50 $\pm$ 2% relative humidity. The effect of the change in test conditions on the water vapor transmission values is shown in Table 3. The values for water vapor transmission and permeability are significantly lower when the tests are run under the ASTM conditions, than under the conditions existing in the previous tests, (2). This probably reflects the higher relative humidity and lower air velocity of the ASTM conditions. The driving force for transmission increases with increasing difference in humidity on each side of the membrane.

Results

The water vapor permeability of 27 membrane liners, including three previously tested, were then determined and the results are presented in Table 4.

The polyester liner, which was the thinnest membrane in the series with a thickness of eight mils, had the highest rate of water vapor transmission. However, its water vapor permeability, which corrects for thickness and is a property of the liner polymer, is in the same range as that of polyvinyl chloride compositions, some of which are considerably more permeable. There is a threefold variation from the lowest permeability to the highest in the case of polyvinyl chloride liners. As a group the polyvinyl chloride liners are the most permeable, confirming the results given in the Second Interim Report (2). The most impermeable materials in this test series are elasticized polyolefin or butyl rubber, both of which have less than one-tenth of the water vapor permeability of polyvinyl chloride. There is a considerable spread in the values for butyl rubber (Table 4) indicating compound differences. The other liner materials are intermediate in water vapor permeability, with a possible twofold variation among them.

Swelling of polymeric compositions, such as that anticipated for polymeric liners exposed to leachate for long periods, generally increases permeability. Consequently, running the permeability tests for long periods should result in some swelling of the test specimens and higher permeability. Table 5 presents such results for 11 liner specimens. Permeability values obtained from the 35th to the 63rd day are compared with those obtained before the 35th day. In all cases, values determined in the 35th to 63rd day interval are higher than those that were determined in the 7-to 28-day interval. Furthermore, the increases tend to follow the respective tendencies of the liner specimens to swell in water. Additional testing of the effect of swelling on permeability is planned with pre-swollen specimens.

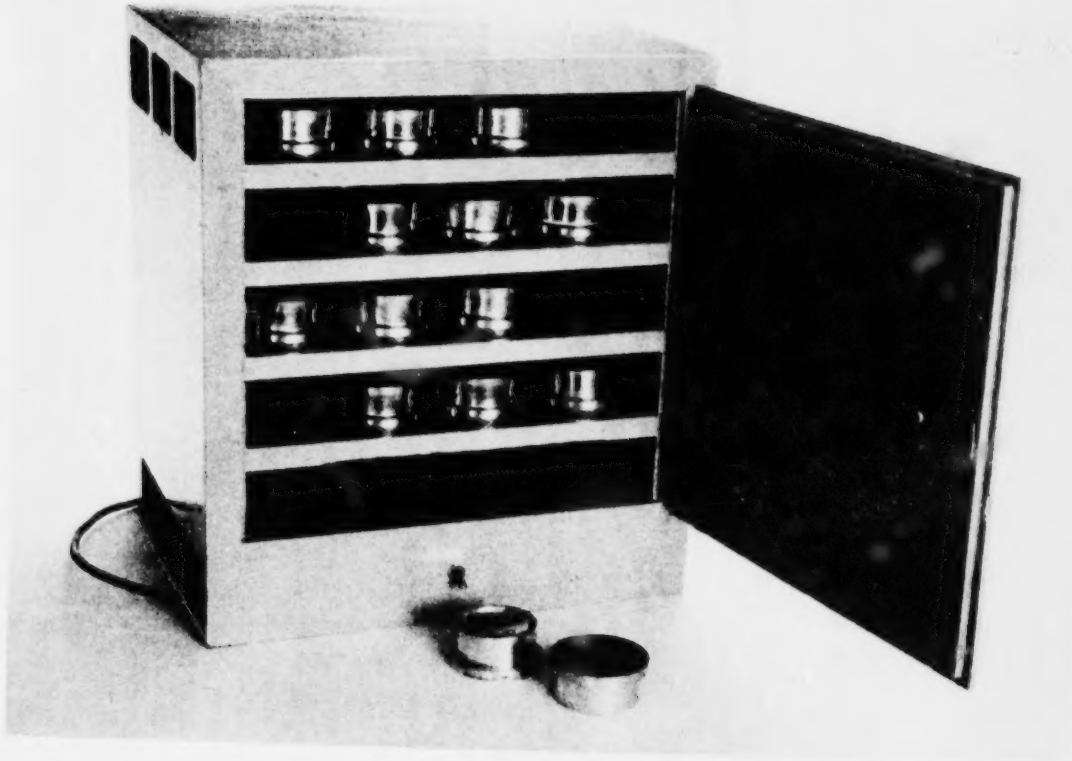

Figure 6. Constant-air-velocity cabinet for holding E96 permeability cups. The cabinet is operated in a constant-humidity room having a temperature of 73°F and a relative humidity of 50%.

TABLE 4. WATER VAPOR PERMEABILITY OF POLYMERIC MEMBRANE LINERS, ASTM E-96, METHOD BW[a]

Polymer	Liner No.	Thickness, mils	Thickness, cm	Test time, days	Rate of water vapor transmission, $g/d \cdot m^2$	Water vapor permeance, 10^{-2} $g/d \cdot m^2 \cdot mmHg$ (metric perm)	Water vapor permeability, 10^{-3} $g/d \cdot m^2 \cdot mmHg \cdot cm$ (metric perm-cm)
Butyl rubber	22	73.3	0.185	49	0.097	0.75	1.39
	57	33.5	0.085	21	0.020	0.17	0.15
Chlorinated polyethylene	12	33.3	0.085	28	0.264	2.10	1.76
	38	32.3	0.082	21	0.361	2.90	2.35
	77	31.0	0.079	21	0.320	2.80	2.10
	86	21.0	0.053	28	0.643	5.10	2.72
Chlorosulfonated polyethylene	3	31.0	0.079	32	0.634	5.00	3.97
	6[b]	37.0	0.094	40	0.422	4.21	3.79
	55	35.0	0.089	42	0.438	3.47	3.09
Elasticized polyolefin	36	28.3	0.072	28	0.142	1.20	0.85
Ethylene-propylene rubber	8	67.0	0.170	28	0.172	1.40	2.52
	18	48.5	0.123	28	0.314	2.49	3.07
	26	38.0	0.097	28	0.327	2.80	2.72
	41	20.0	0.051	21	0.270	2.15	1.09
	83	37.0	0.094	28	0.190	1.50	1.42
Neoprene	9	61.0	0.159	21	0.237	1.90	2.89
	42	20.0	0.051	42	0.304	24.1	1.22
	43	31.5	0.080	28	0.448	3.90	3.12
	82	61.2	0.155	63	0.240	2.00	3.11
Polyester elastomer	75	8.0	0.020	21	10.50	91.0	18.2
Polyvinyl chloride	11	30.0	0.076	28	1.85	16.0	12.2
	17	20.0	0.051	35	2.97	24.0	12.0
	19	21.0	0.054	42	2.78	22.0	11.8
	40	32.5	0.083	42	4.17	33.0	27.3
	59	33.0	0.084	21	4.20	36.0	30.2
	88	20.5	0.052	35	2.94	23.0	12.1
	89	11.0	0.028	35	4.42	35.0	9.77

[a]Average temperature, 72°F; average relative humidity, 42%.
[b]Fabric-reinforced.

TABLE 5. EFFECT OF TEST TIME ON WATER VAPOR PERMEABILITY OF MEMBRANES IN E96-BW TEST

Polymer	Liner no.	Permeability metric perm·sec x 10^{-3} 7-28 days[a]	35-63 days[b]	% Increase
Butyl rubber	57	0.18	0.22	22
Chlorinated polyethylene	77	2.63	2.87	9
Chlorosulfonated polyethylene	6[c]	2.07	2.57	24
Elasticized polyolefin	36	1.09	1.18	8
Ethylene propylene rubber	8	2.87	3.11	8
	26	3.40	3.68	8
Neoprene	43	3.90	5.14	32
	82	1.61	38.5	139
Polyester elastomer	75	1.14	1.18	3
Polyvinyl chloride	11	15.25	17.09	12
	59	38.21	40.98	7

[a] Temperature, 72°F; relative humidity, 54%, ΔP, 9.23.
[b] Temperature, 74°F; relative humidity, 55%; ΔP, 9.65.
[c] Fabric reinforced.

BAG TEST FOR ASSESSING MEMBRANE LINER MATERIALS

As the permeability of membrane liners to water and to other leachate components under landfill conditions is not necessarily reflected by the water vapor permeability as determined by E-96, other methods of assessing the permeability of liner materials are, therefore, being investigated:

1. Sealing leachate into bags fabricated from the liner membranes and immersing these bags in deionized water. The permeation of dissolved leachate components into the deionized water can be observed through pH and conductivity measurements and changes in weight of the filled bags.

2. Testing liner specimens in a top-pressure permeameter in which air pressure of one or more atmospheres can be placed on a layer of water or leachate covering a liner material.

3. Determining the permeabilities of membrane liners after swelling specimens in water at room temperature and at 70°C to simulate long exposure to leachate.

The first of these methods is discussed and results are presented.

Initial experiments carried out with various heat-sealable liner materials demonstrated the feasibility of the test procedure. Two series of bags were then fabricated of heat-sealable lining materials. One set was filled with leachate and the second set with 5% sodium chloride. The liner materials in these tests include the following polymers: chlorinated polyethylene, chlorosulfonated polyethylene, elasticized polyolefin, polyester elastomer and polyvinyl chloride (3 different membranes).

Figure 7 shows a schematic of the bag assembly and Figure 8 is a photograph of the bags and the necessary testing equipment.

The individual bags for the leachate were 20 x 14 cm, which gave an exposable surface of approximately 560 cm^2. For the sodium chloride solution the bags were 17 x 12 cm, which yielded an exposable surface of approximately 400 cm^2.

Each bag was constructed with a neck through which the test fluid is introduced. After the bag is filled, the neck is heat sealed. Leachate, (100 ml), of the composition shown in Table 6, and 305-490 ml of 5% salt solution were added to the respective bags.

TABLE 6. CHARACTERISTICS OF LEACHATE IN BAGS[a]

Property	Value
Total solids, %	2.0[b]
Total volatile solids, %	1.1[b]
Chemical oxygen demand, g/l	35.7[b]
Total volatile acids, g/l	15.2[b]
pH	5.15[b]
Conductivity, µmho	11,500

[a] Amount of leachate in each bag is 100 ml. Samples were taken from the blend of leachates collected on November 8, 1976.

[b] Average value for the leachates taken from the 12 generators.

The following tests were performed during the exposure of these bags:

1. The deionized water was tested periodically for pH, conductivity, and for the odor of butyric acid, in the case of the inner bags containing leachate.

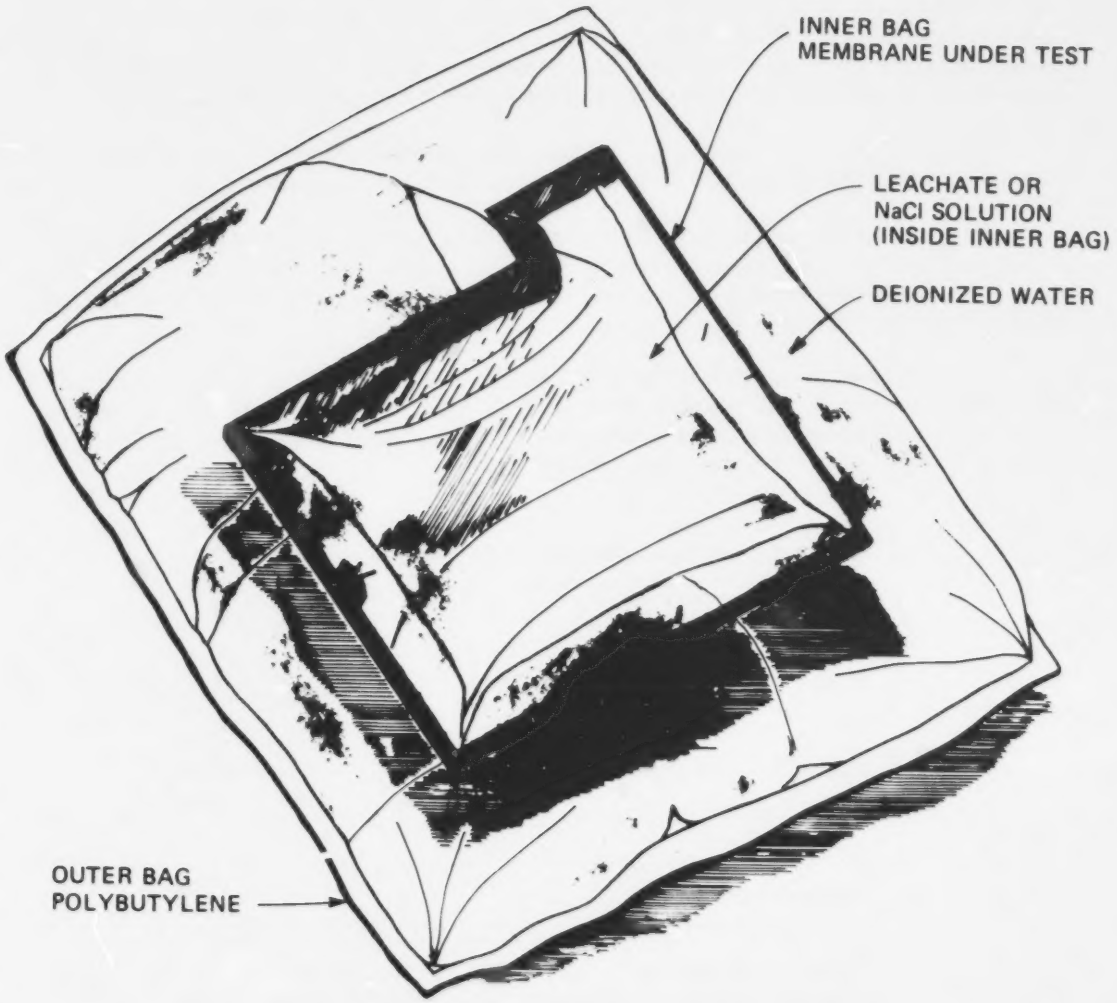

Figure 7. Schematic of osmosis bag assembly, showing inner bag made of membrane material under test. The inner bag is filled with leachate or 5% salt solution and sealed at the neck. The outer polybutylene bag, which can be easily opened, is filled with deionized water. The water in the outer bag is monitored for pH and conductivity; the inner bag is monitored for weight change.

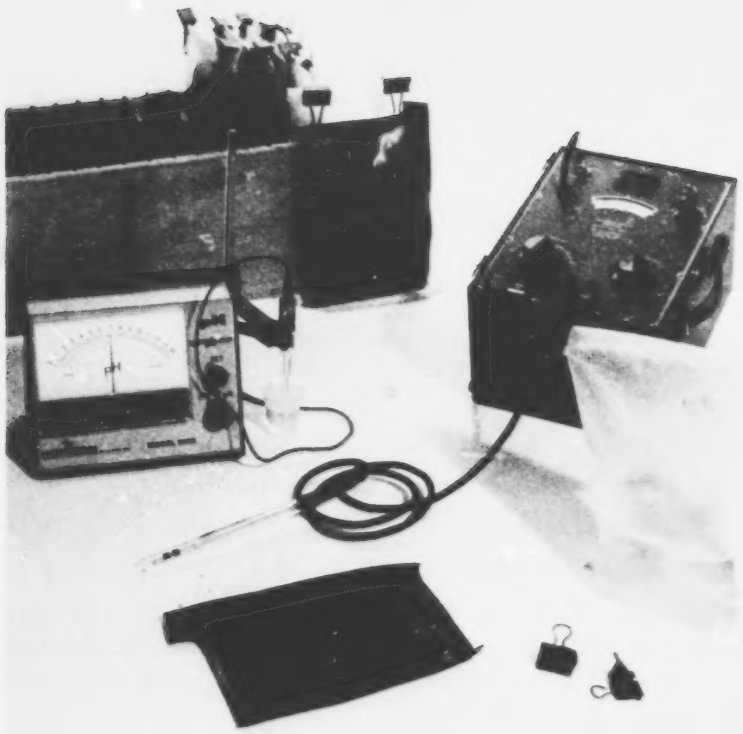

Figure 8. Osmosis bag and auxiliary equipment for monitoring.

2. The bags containing the test fluid were removed periodically from the water and weighed.

Results of the tests after extended exposures are given in Tables 7-10.

In the case of the bags containing leachate, after 500 days of exposure it was apparent that there was movement through the liner by both the water and the dissolved ingredients of the leachate (Table 7). An increase in electrical conductivity occurred, indicating the permeation of some ions from the leachate into the deionized water. Also, there was an increase in the weight of the bags containing the leachate, indicating permeation of water into the bags containing leachate. In this series, the elasticized polyolefin yielded the lowest transmission of water and of dissolved components and the chlorinated polyethylene appears to be the most permeable. The order of the liner materials is shown in Table 8 for increasing conductivity of the deionized water and for the increase in the weight of the bags shown in Table 8.

TABLE 8. TESTS OF BAGS CONTAINING LEACHATE - ORDER OF LINERS BY INCREASING BAG WEIGHT AND BY CONDUCTIVITY OF DEIONIZED WATER

Order of increase	Conductivity of deionized water	Weight of bag
1	Elasticized polyolefin (#36)	Elasticized polyolefin (#36)
2	Polyvinyl chloride (#59)	Polyvinyl chloride (#11)
3	Polyvinyl chloride (#11)	Polyvinyl chloride (#59)
4	Polyester elastomer (#75)	Polyvinyl chloride (#17)
5	Chlorinated polyethylene (#77)	Polyester elastomer (#75)
6	Polyvinyl chloride (#17)	Chlorinated polyethylene (#77)

Somewhat similar results were obtained when the inner bags were filled with 5% sodium chloride solution (Table 9). Again, the elasticized polyolefin was the most impermeable of the liners and one of the polyvinyl chloride membranes (#11) was the second most impermeable. The order for the liners in this set is shown in Table 10 for increasing conductivity of the deionized water and increasing weight in the bags.

TABLE 7. TESTS OF MEMBRANE LINER BAGS FILLED WITH LEACHATE - PERMEABILITY OF MEMBRANES TO WATER AND TO IONS DUE TO OSMOSIS

Polymer	Liner no.	Original values			Values at 70 days			Values at 500 days		
		pH[b]	Conductivity[b], μmho	Weight of filled bag, g	pH[b]	Conductivity[b], μmho	Weight increase[c], g	pH[b]	Conductivity[b], μmho	Weight increase[c], g
Chlorinated polyethylene	77	5.7	5.2	170.91	5.8	29.7	1.68	6.5	124.0	4.74
Elasticized polyolefin	36	5.1	4.3	142.63	5.0	9.82	-0.07	4.5	17.8	0.22
Polyester elastomer	75	4.0	20.5	112.25	3.5	73.0	0.58	6.4	50.0	2.95
Polyvinyl chloride	11	5.8	6.0	166.88	4.4	30.9	0.41	6.0	32.0	1.12
Polyvinyl chloride	17	5.0	13.3	138.28	2.9	310.1	0.33	2.8	325.0	1.37
Polyvinyl chloride	59	5.7	5.9	170.14	3.8	61.5	0.97	6.3	23.2	1.21
Blank	--	5.5	1.33	--	5.7	1.75	--	4.3	11.6	--

[a]Area of each bag exposed to test fluid is 560 cm^2.
[b]pH and conductivity of deionized water outside the bags containing leachate.
[c]Weight increase of bags containing leachate.

TABLE 9. TESTS OF MEMBRANE LINER BAGS FILLED WITH 5% NaCl SOLUTION - PERMEABILITY OF LINERS TO WATER AND TO IONS DUE TO OSMOSIS

Polymer	Liner no.	Original values		Values at 113 days		Values at 200 days	
		Conductivity[b], μmho	Weight of filled bag, g	Conductivity[b], μmho	Weight increase[c], g	Conductivity[b], μmho	Weight increase[c], g
Chlorinated polyethylene	77	1.92	370.91	23.3	1.01	31.2	+1.56
Chlorosulfonated polyethylene	6	3.48	391.02	86.0	1.36	113.0	+2.20
Elasticized polyolefin	36	1.51	329.50	9.5	-0.02	10.9	+0.06
Polyester elastomer	75	1.62	424.35	22.9	2.61	30.0	+5.30
Polyvinyl chloride	11	1.67	479.81	13.7	0.26	15.3	+0.69
Polyvinyl chloride	59	1.77	537.80	19.5	1.07	21.5	+1.86
Blank	--	0.63	--	7.8	--	6.6	--

[a]Area of bag exposed to test fluid was 480 cm^2.
[b]Conductivity of deionized water outside the test bags.
[c]Weight increase of bags.

TABLE 10. TEST OF BAGS CONTAINING 5% SALT SOLUTION - ORDER OF LINERS BY INCREASING BAG WEIGHT AND BY CONDUCTIVITY OF DEIONIZED WATER

Order of increase	Conductivity of deionized water	Weight of bag
1	Elasticized polyolefin (#36)[a]	Elasticized polyolefin (#36)
2	Polyvinyl chloride (#11)	Polyvinyl chloride (#11)
3	Polyvinyl chloride (#59)	Chlorinated polyethylene (#77)
4	Polyester elastomer (#75)	Polyvinyl chloride (#59)
5	Chlorinated polyethylene (#77)	Chlorosulfonated polyethylene (#6)
6	Chlorosulfonated polyethylene (#6)	Polyester elastomer (#75)

[a]Membrane liner identification number.

After the completion of individual tests, the bags will be cut, physical properties of the liner materials will be determined, and the leachate will be analyzed.

This may be a good laboratory test for assessing membrane liner materials. It is planned to extend this work to include additional membrane liners, including rubber membranes which must be cemented. A similar series of tests is now underway on various hazardous wastes.

WATER ABSORPTION OF MEMBRANE LINER MATERIALS

The swelling of a rubber or plastic membrane liner generally results in a reduction of desired physical properties as well as an increase in permeability. Severe swelling over a long period of time could ultimately cause the failure and non-performance of a polymeric liner material. When materials are evaluated for specific liner applications their swelling should be studied under various conditions.

During the first year of exposure in the simulated landfills, some of the specimens showed significant absorption of leachate. A concurrent test run in the laboratory of some of the same liner materials in water showed similar absorption, although the order of increasing swell was not the same. These data were presented in the Second Interim Report (2), along with absorption data run at 100°C. Raising the test temperature during immersion accelerated the rate of water absorption. It was hoped that a short-term test of two hours would indicate the swelling characteristics of a liner material, but the results did not correlate with either the room temperature data or with the cell exposure.

The temperature used was felt to be too high. Consequently, another series of swell tests was run, in accordance with ASTM D570, at room temperature and at 70°C. The results of swelling up to 100 weeks are shown in Table 11. Generally, the immersion at room temperature and at 70°C resulted in essentially the same order of increasing swelling; the correlation was significantly better than immersion at 100°C, as shown in Table 12.

TABLE 12. ORDER OF INCREASED SWELLING IN WATER AT ROOM TEMPERATURE AND AT 70°C[a]

Order of increased swelling	At room temperature	At 70°C
1	Polyvinyl chloride (#11)	Polyester elastomer (#75)
2	Polyester elastomer (#75)	Elasticized polyolefin (#36)
3	Ethylene propylene rubber (#8)	Ethylene propylene rubber (#26)
4	Ethylene propylene rubber (#26)	Ethylene propylene rubber (#8)
5	Polyvinyl chloride (#59)	Polyvinyl chloride (#59)
6	Elasticized polyolefin (#36)	Polyvinyl chloride (#11)
7	Butyl rubber (#57)	Butyl rubber (#57)
8	Chlorinated polyethylene (#77)	Chlorinated polyethylene (#77)
9	Chlorosulfonated polyethylene (#6)	Neoprene (#82)
10	Neoprene (#43)	Chlorosulfonated polyethylene (#6)
11	Neoprene (#82)	Neoprene (#43)

[a]ASTM D570.

One of the major differences in the results obtained at the two temperatures was in one of the polyvinyl chloride liners which at room temperature yielded the lowest swelling, but at 70°C was sixth in swelling. The materials that had the lowest swell were polyvinyl chloride, elasticized polyolefin, and ethylene propylene rubber. Those swelling the most were neoprene, chlorosulfonated polyethylene, and chlorinated polyethylene. These exposures are being continued and will be supplemented by limited physical testing of the highly swollen materials to determine the relationship of physical properties to the degree of swelling.

TABLE 11. WATER ABSORPTION OF SELECTED MEMBRANE LINER MATERIALS AT ROOM TEMPERATURE AND AT 70°C[a]

Polymer	Liner No.	Water absorbed, % by weight: At room temperature, 1 week	At room temperature, 11 weeks	At room temperature, 44 weeks	At room temperature, 100 weeks	At 70°C, 1 day	At 70°C, 1 week	At 70°C, 11 weeks	At 70°C, 44 weeks	At 70°C, 100 weeks
Butyl rubber	57	0.82	3.22	4.50	6.4	2.04	4.62	17.54	53.9	103.2
Chlorinated polyethylene	77	1.63	5.53	10.2	12.5	3.04	15.9	58.4	140.0	179.3
Chlorosulfonated polyethylene	6	3.44	6.97	10.9	16.3	5.68	22.1	131.0	245.6	370.5
Elasticized polyolefin	36	0.39	0.52	0.0	4.5	0.24	0.36	0.45	0.57	8.7
Ethylene propylene rubber	8	0.50	1.30	1.56	2.25	0.42	1.11	3.55	10.8	17.8
	26	1.20	1.84	1.49	2.56	0.74	1.44	4.52	11.20	17.4
Neoprene	43	3.80	13.62	37.8	75.1	3.89	14.1	107.0	240.0	(b)
	82	2.43	8.29	18.5	32.1	2.49	8.11	47.4	191.4	295.0
Polyester elastomer	75	1.07	1.05	0.67	1.31	1.18	1.28	1.10	0.72	0.22
Polyvinyl chloride	11	1.29	1.10	0.70	1.25	1.51	5.59	12.13	39.2	87.4
	59	1.59	2.34	2.43	2.98	2.09	4.87	8.25	24.0	25.5[c]

[a] ASTM D570-63 specimens 1 x 2 in. in deionized water.
[b] Specimens began to disintegrate between 44th and 69th weeks.
[c] Specimens have become hard, indicating loss of plasticizer.

The immersion tests described earlier also furnish information for comparison with these swelling data. In Table 13, for example, liners that have been swollen in both water and leachate are compared. The liner materials immersed in the leachate swelled significantly more in 32 weeks than did the same materials immersed in deionized water for 44 weeks. This difference is probably due to the organic content of the leachate.

TABLE 13. COMPARISON OF THE SWELLING OF MEMBRANE LINING MATERIALS IMMERSED IN WATER AND IN LEACHATE

Polymer	Liner no.	Swelling, %	
		In water for 44 weeks	In leachate for 32 weeks
Chlorosulfonated polyethylene	6	10.9	13.3
Elasticized polyolefin	36	0	0.1
Ethylene propylene rubber	8	1.6	6.0
Polyester elastomer	75	0.67	2.0
Polyvinyl chloride	11	0.70	2.9

Extended exposures at 70°C were run to determine whether there is a tendency on the part of liner materials to reach a plateau of swelling with respect to time. Chlorinated polyethylene and ethylene propylene rubber appeared to have essentially plateaued. One of the polyvinyl chloride liners appeared to have come to a maximum value; however, it hardened, presumably from loss of plasticizer. The neoprene and chlorosulfonated polyethylene specimens appeared to continue to swell. The elasticized polyolefin absorbed little during the first 400 days; after that, it began to swell. This swelling test of the liners is being continued. Also, one of the three specimens of each of the polyvinyl chloride liners will be analyzed for loss of plasticizer.

MONITORING THE LEACHATE GENERATORS

In November 1975, after one year of operation. 12 of the 24 original leachate generators - liner exposure cells were disassembled and the exposed liner specimens were recovered and tested (2, 4). Monitoring of the 12 remaining generators has continued:

1. Every two weeks, 2 gal tap water were added to simulate 1 in. rainfall. Over the year, this is equivalent to 26 in. of rain entering the landfill, a condition which exists in the Pacific northwest.

2. Records were made of leachate output, ambient temperature, temperature within two generators, and level of refuse and cover within the generators.

3. The leachate was analyzed approximately once a month for percent total solids, percent volatile solids, total volatile acids, chemical oxygen demand, and pH.

4. The seepage of the leachate through the liner was measured.

Collection of Leachate

The leachate is collected continuously in bags prepared from polybutylene. These bags replaced the polyethylene bags that failed at the heat-sealed seams. A constant head of 1 ft of leachate was maintained by allowing the leachate to pass through an inverted U-tube placed in the outflow line at 1 ft above the lining. During recent months, gas was generated in the bases and bags causing the bags to inflate. To prevent a buildup of excess pressure and failure of the bags, relief valves were installed, as shown in Figure 9. Since the installation of these valves there has been no leakage of the bags.

Leachate Characteristics

The leachate has been analyzed on approximately a monthly basis since the cells reached "field capacity" in November 1974. Average analytical results for solids, pH, volatile acids, and chemical oxygen damand are presented in Figures 10 through 13, respectively. During the first year of operation, the characteristics of the leachate remained constant except the volatiles acid content, which increased. Since that time, there has been a reduction in the solids, total volatile acids, and chemical oxygen demand, and a rise in pH. The early leachate contained a relative high concentration of butyric acid, which seems to be essentially absent in the more recent leachate.

Consolidation of Refuse

During the course of the operation of the generators, considerable consolidation of the shredded refuse has occurred within the generators, as shown in Figure 14. This consolidation has been essentially linear with time, although there are indications that this consolidation is slowing down. At the end of 180 weeks of leachate production, the consolidation averages about 16% for the refuse in the 12 generators.

Seepage of Leachate

One of the primary design features of the leachate generator - exposure cells is the capability of their functioning as large permeameters. The liner specimens were sealed in the bases of the generators to prevent by-passing of the liners.

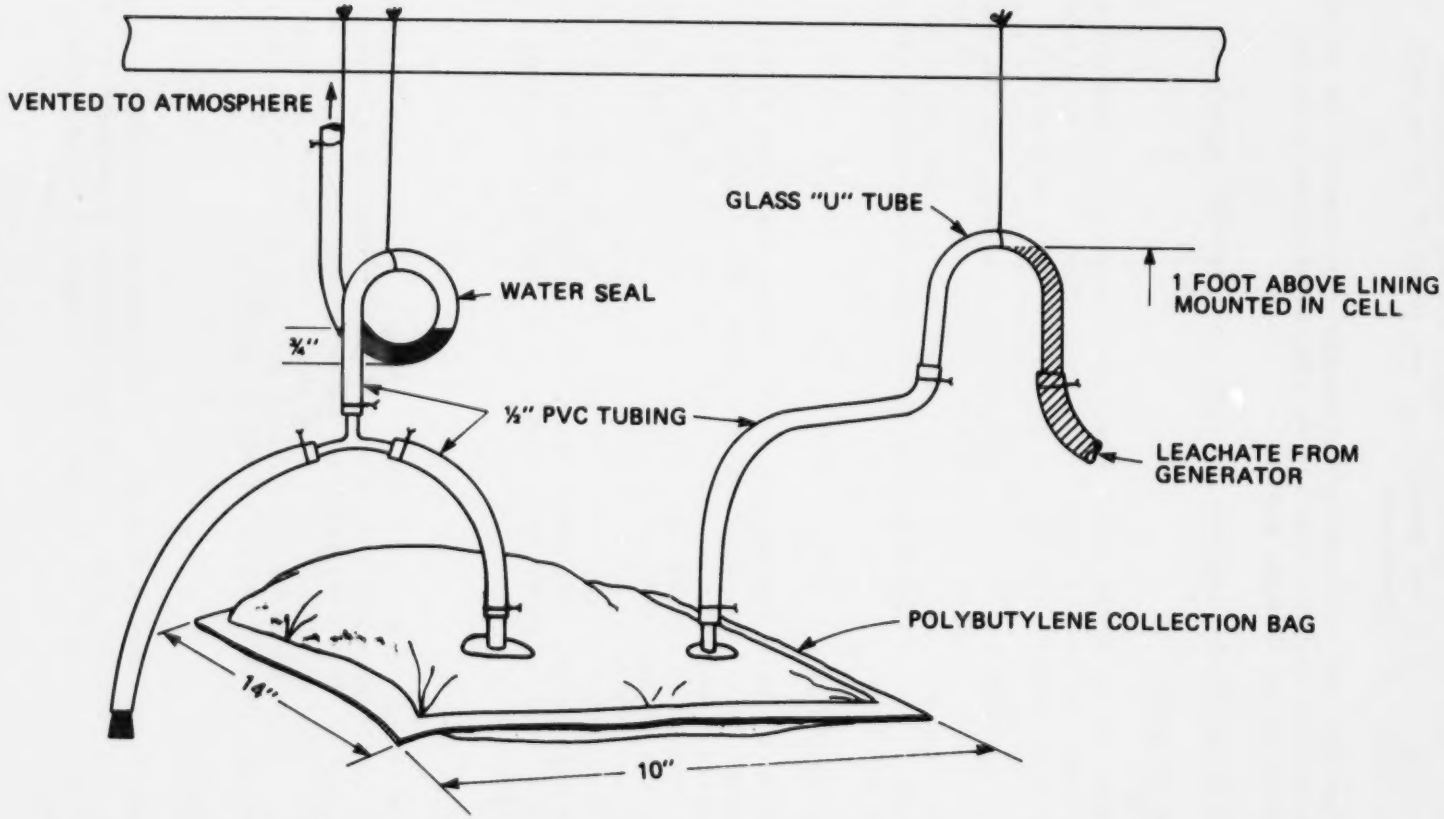

Figure 9. Leachate collection bag with water seal and vent to prevent excessive gas pressure build-up in the bag. The seal prevents air from entering the bag and oxidizing the leachate.

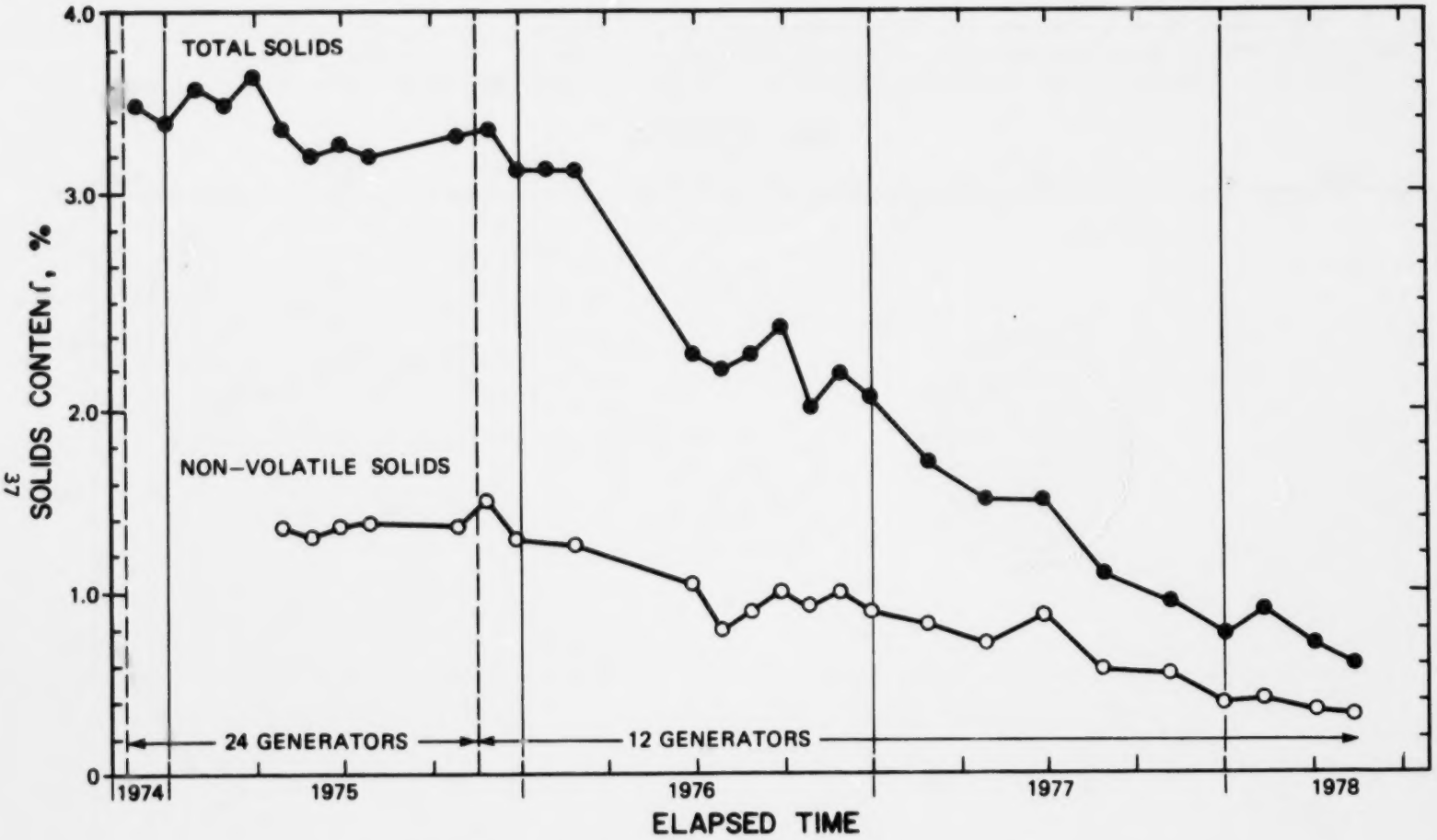

Figure 10. Average solids contents of the leachate produced in the generators, November 1974 - May 1978. The data for November 1974 - November 1975 are the averages for the leachate from 24 generators. Twelve generators were disassembled in November 1975 and, consequently, the data for December 1975 - May 1978 are the averages for the leachates from the 12 remaining generators.

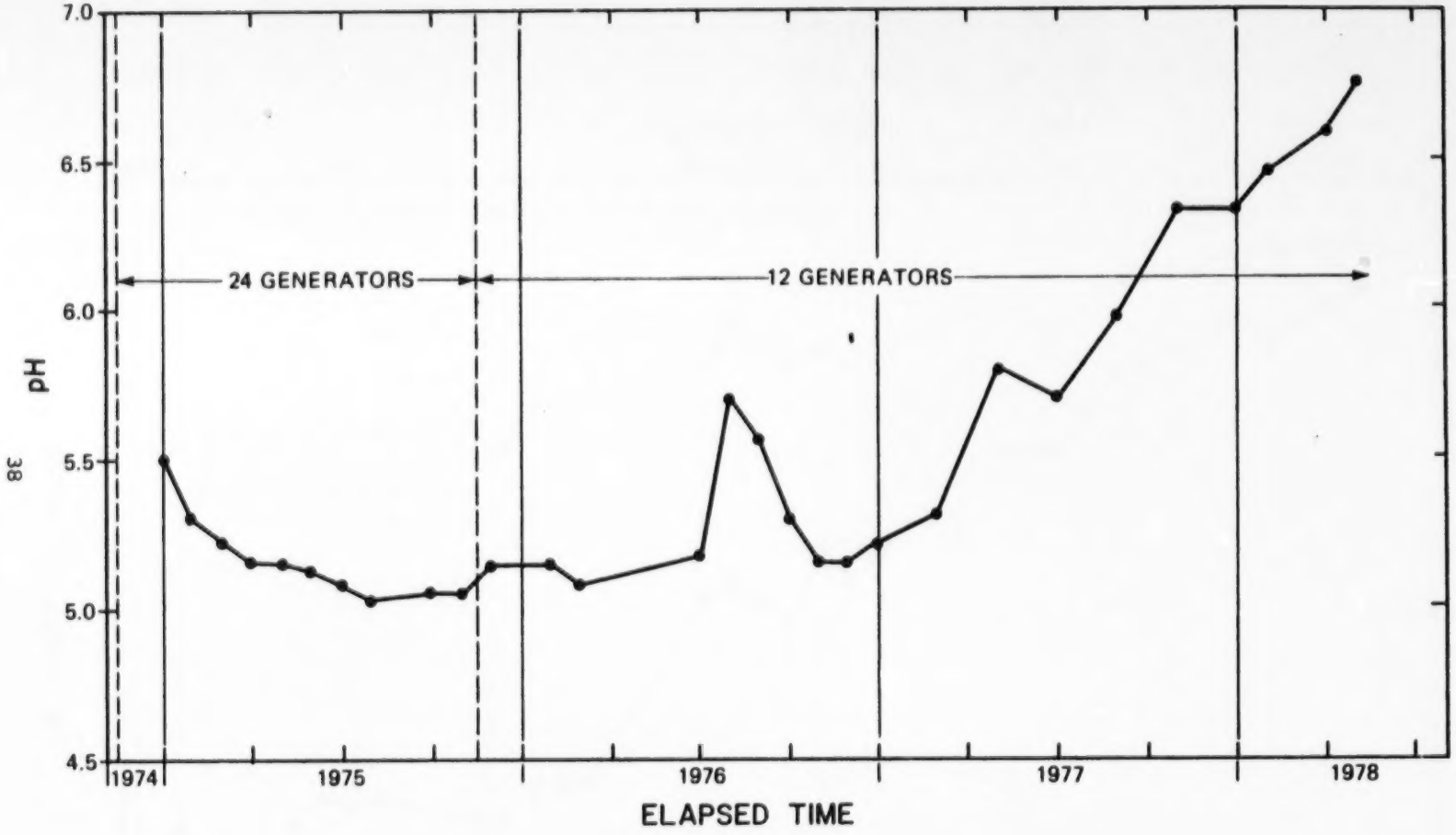

Figure 11. Average pH of the leachate produced in the generators, November 1974 - May 1978. The data from November 1974 - November 1975 are the averages for the leachates from 24 generators. The data for December 1975 to May 1978 are the averages for the leachate from 12 generators.

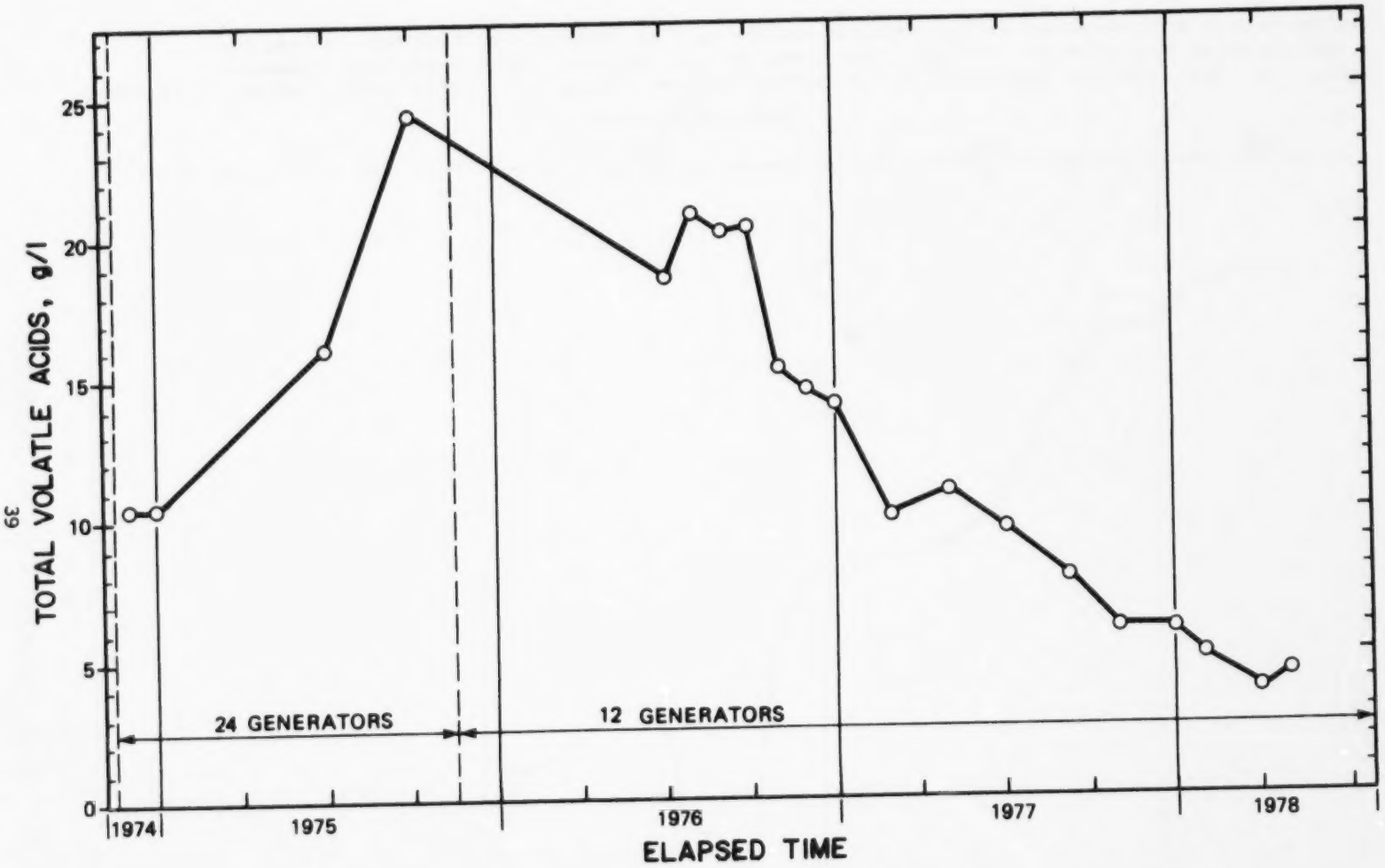

Figure 12. Average total volatile acids content (TVA), as acetic acid, of the leachate produced in the generators, November 1974 - May 1978. The data for November 1974 - November 1975 are the averages for the leachates from 24 generators. The data for December 1975 - May 1978 are the averages for the leachates from 12 generators.

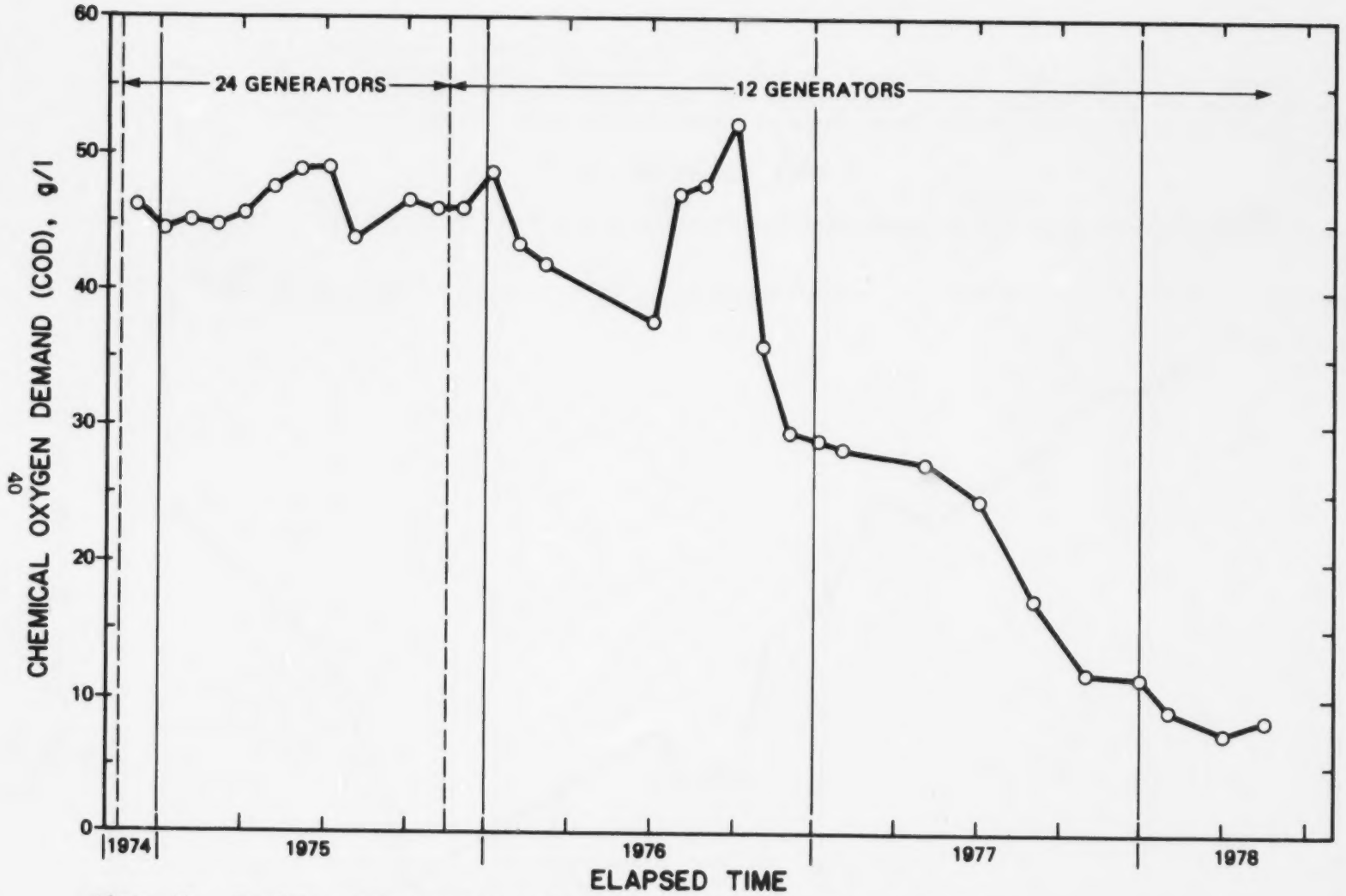

Figure 13. Chemical oxygen demand (COD) of the leachate produced in the generators, November 1974 - May 1975. The data for November 1974 - November 1975 are the averages for the leachates from 24 generators. The date for December 1975 through May 1978 are the averages for the leachates from 12 generators.

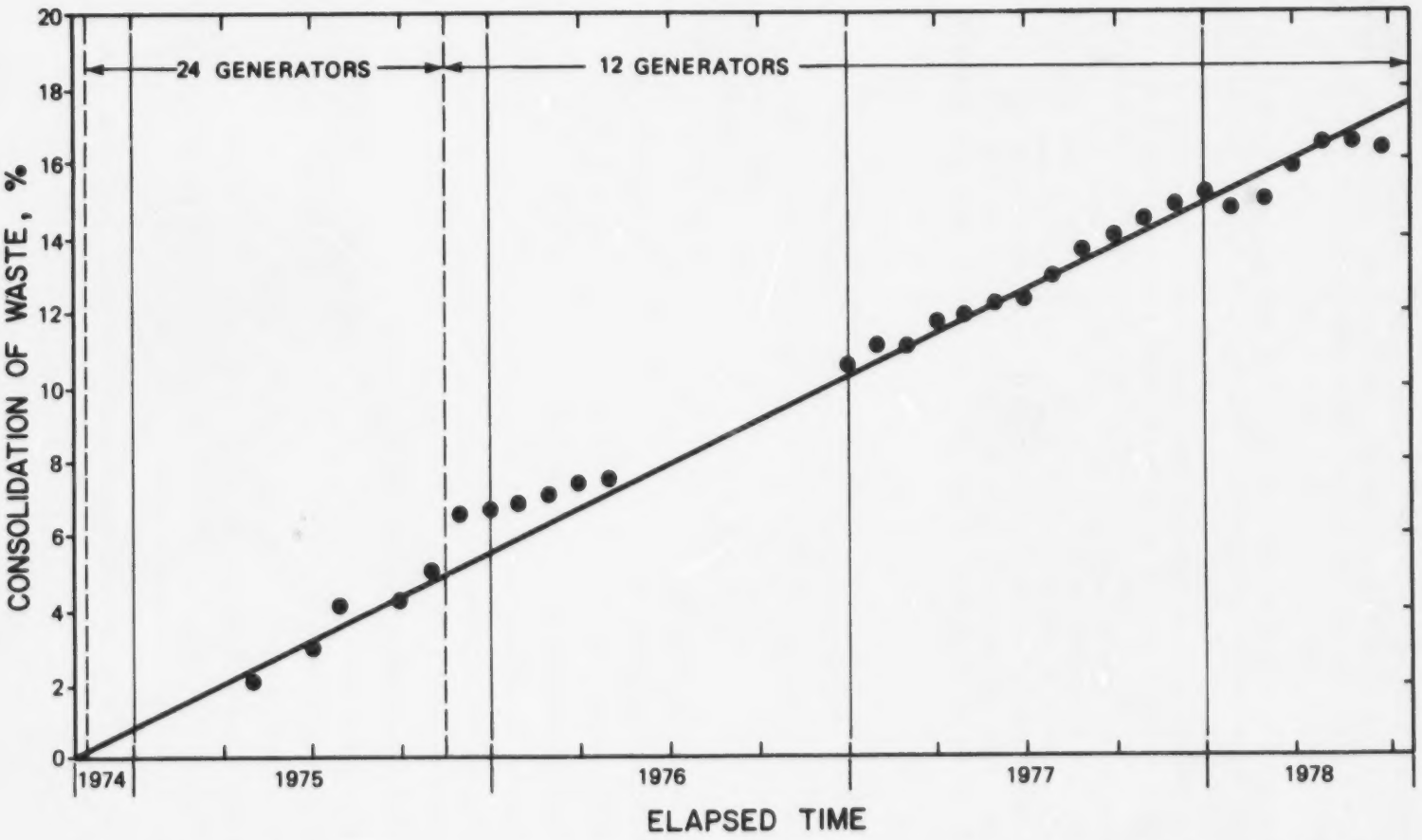

Figure 14. The average refuse consolidation in the leachate generators, November 1974 - May 1978. The data for November 1974 - November 1975 are averages for the refuse in the 24 generators. The data for December 1975 and later are the averages for the consolidation in 12 generators.

A constant head of one ft of leachate is maintained above the liner to supply a driving force for the fluids through the liner specimens. Permeability of the liner can, therefore, be determined by collecting the leachate below it.

The results of the cumulative collection of the leachate below the liner specimen is reported in Table 14. The seals in two of the generators, #1 and #3, in which polyethylene and butyl rubber are being exposed respectively, appear to have failed. The epoxy resin that was used to make the seal probably disintegrated in much the same fashion as occurred in two of the first 12 generators that were previously dismantled. The mercaptan epoxy resin that was used to achieve rapid set does not have high chemical resistance and is sensitive to off-ratios between the resin and hardener. Although the leachate is being collected from drains below these liners, it is still being ponded on the liners to keep them immersed in leachate. The remaining cells appear to be functioning properly with only three showing seepage; i.e., polyvinyl chloride, soil cement, and soil asphalt.

TABLE 14. CUMULATIVE COLLECTION OF LEACHATE BELOW LINERS MOUNTED IN BASES OF GENERATORS[a]

Generator no.	Liner Material	Amount of leachate collected, kg.
1	Polyethylene (#21)[b]	(c)
2	Polyvinyl chloride (#17)	1.27
3	Butyl rubber (#7)	(c)
4	Chlorosulfonated polyethylene (#6)	0
5	Ethylene propylene rubber (#18)	0
6	Chlorinated polyethylene (#12)	0
7	Paving asphalt concrete (2 in. thick)	0
8	Hydraulic asphalt concrete (2 in. thick)	0
9	Soil cement (4.5 in. thick)	0.23
10	Soil asphalt (4 in. thick)	1.33
11	"Cat" blown asphalt membrane (0.25 in. thick)	0
12	Emulsion asphalt on fabric (0.25 in. thick)	0

[a] From November 21, 1974, to May 31, 1978.
[b] Membrane liner identification number.
[c] Leachate appears to be by-passing the liners and is being collected from drains below the liners.

At the conclusion of the exposure (now planned for June 1979), it will be possible to determine whether there has been any failure in the liners or if, in fact, the epoxy resin seal disintegrated.

RECOVERY AND TESTING OF SAMPLES OF A POLYVINYL CHLORIDE LINER FROM A DEMONSTRATION LANDFILL

Information from the field regarding the performance of artificial lining materials on long exposure to sanitary landfill leachate has been very limited. First, such use for these liners, particularly the polymeric membranes, is relatively new, dating from the early 1970's. Second, effective and economic methods of retrieving specimens and repairing linings at the bottoms of landfills have not been developed.

A demonstration landfill in Crawford County, Ohio, placed in the spring of 1971, was lined with a polyvinyl chloride liner. The liner from this landfill was relatively accessible as the total fill contained one lift of 8 ft of refuse and was about 12 ft deep, including the cover. This demonstration landfill had been designed to compare conventionally processed solid waste with rough and compacted wastes. The various types of refuse had been placed in essentially waterproof cells lined with plastic membranes. The effect of water content on consolidation and decomposition of the refuse was to be determined. However, all of the cells were flooded with water in a heavy rainfall just before the fill was closed. Thus, the original objectives could not be met and the project was terminated.

In view of the relative accessibility of the liner, the landfill was opened in May 1977, after six years, and the membrane liner was recovered. The cells appeared to have retained the water. The condition of the refuse did not appear to be typical of sanitary landfills. The odor was mild, and the refuse showed little deterioration. The samples of liners recovered from the cells appeared to be in excellent condition with little difference apparent between samples taken from the top of the cell, above the refuse, and those taken from the bottom, below the refuse. The top liner had been under 3 ft of clay cover, and the bottom liner had been under about 2 ft of clay and was on top of pea gravel. Both liners had taken the shape of soil and gravel without breaking. The depressions were as much as 6 in. deep in a 1 ft area in the exposed top liner.

These samples were analyzed along with a sample of polyvinyl chloride sheeting that was thought to have been in the same lot as the material used for lining the cells. However, the results, (Table 15) show that the two specimens taken from the fill were very similar and considerably different in composition from the unexposed sample, indicating that it was not a control for the liner. As Table 16 and Appendix B show, the amount of swelling and the decrease in properties of the lining were within the spread of values observed in the leachate immersion test for seven polyvinyl chloride materials. The specimen taken from the bottom was probably not in

TABLE 15. ANALYSES OF POLYVINYL CHLORIDE LINER RECOVERED FROM DEMONSTRATION LANDFILL IN CRAWFORD COUNTY, OHIO

Property	Composition		
	Unexposed[a] liner (#95)	Liner from top of fill (#96)	Liner from bottom of fill (#97A)
Volatiles (2 h at 105°C), %	0.10	0.41	1.33
Specific gravity (dry basis)	1.379	1.260	1.265
Ash (dry basis), ASTM D297, %	10.26	6.14	6.01
Extractables, ASTM D3421[b], %	7.54	34.10	34.43
Pyrolysis[c]:			
Polymer and organic content, %	80.6	87.0	89.0
Polymer content, %	73.1	52.9	54.6
Carbon black, %	8.6	6.7	4.4
Ash, %	10.9	6.4	6.8

[a] Shelf, indefinite exposure in shop.

[b] Modified: 20 h refluxing with mixed solvent of carbon tetrachloride (CCl_4):methyl alcohol (CH_3OH), 2:1.

[c] Test method: Reference 6.

direct contact with the leachate in the fill during the 6 years it was in place. The 2 ft soil layer above the liner was a highly impermeable clay having a permeability coefficient of 1.4×10^{-7} cm/sec. The clay layer and the weak leachate created a situation that was not typical of what might be anticipated for a liner in a fullscale landfill.

TABLE 16. PROPERTIES OF POLYVINYL CHLORIDE LINER RECOVERED FROM A DEMONSTRATION LANDFILL IN CRAWFORD COUNTY, OHIO

Property	Test method	Liner from top of fill (#96)		Liner from bottom of fill (#97A)	
		Machine	Transverse	Machine	Transverse
Thickness, mils	--	30	--	28	--
Tensile strength,psi	ASTM D412	2665	2600	2550	2475
Elongation at break, %	ASTM D412	340	360	325	350
Set at break, %	ASTM D412	66	79	55	70
S-100, psi	ASTM D412	1290	1245	1185	1085
S-200, psi	ASTM D412	1830	1750	1785	1605
S-300, psi	ASTM D412	2245	2300	2400	2205
Tear strength, ppi	ASTM D624	374	370	343	341
Hardness (Duro A), instant	ASTM D2240	77	--	78	--
Puncture resistance, lb	Fed Std 101 -B-2065	41.4	--	37.3	--
Elongation, in.		0.66	--	0.65	--
Seam strength (shear), ppi	ASTM D413	49.5	--	45.5	--
Locus of failure		SE[a]	--	BRK[b]	--

[a]Break at seam.
[b]Break in tab.

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APPENDIX A. PROPERTIES OF UNEXPOSED POLYMERIC MEMBRANES IN PROJECT

Item[a]	Direction of test	Chlorinated polyethylene				Chlorosulfonated polyethylene		
Liner No.[b]		12	38	77	86	3[c]	6[c]	85
Thickness, mils	-	31	32	29	22	31	32	33
Tensile strength, psi	Machine	2460	2190	2055	1845	1710	1770	2345
	Transverse	2080	2000	2340	1510	1430	1610	2055
Elongation at break, %	Machine	300	340	325	355	580	240	260
	Transverse	520	505	480	595	640	225	325
Set at break, %	Machine	199	192	140	208	370	78	167
	Transverse	230	201	160	235	380	79	192
S-100, psi	Machine	1220	1345	1240	870	670	990	1150
	Transverse	520	565	560	275	520	895	750
S-200, psi	Machine	1820	1640	1540	1210	850	1715	2130
	Transverse	840	770	820	405	620	1445	1410
S-300, psi	Machine	2460	2005	1955	1575	1030	-	-
	Transverse	1200	1065	1205	605	760	-	2020
Tear strength, ppi	Machine	270	252	273	187	290	317	308
	Transverse	240	213	239	178	270	287	277
Hardness, Duro A:								
Instant reading	-	85	82	87	76	86	79	83
10-sec. reading	-	77	76	80	67	83	75	79
Puncture resistance, lb	-	47.0	47.8	43.9	20.9	25.4	34.4	47.8
Elongation, in.	-	1.04	0.86	0.94	0.91	1.16	0.57	0.86
Specific gravity	-	1.360	1.336	1.362	1.377	1.433	1.343	1.311
Ash (dry basis), %	-	14.40	11.83	12.56	17.37	33.45	3.35	4.02
Volatiles, %	-	0.10	0.24	(d)	0.05	0.84	0.29	0.92
Exposure tests[e]	-	P,S,I	I	L,N	I	S,I	P,S,I,N	I

See footnotes at end of table.

APPENDIX A (Continued). PROPERTIES OF UNEXPOSED POLYMERIC MEMBRANES IN PROJECT

Item[a]	Direction of test	Ethylene propylene rubber					Butyl rubber
Liner No.[b]	-	8	18	83[c]	91	41	44
Thickness, mils	-	62	49	39	37	20	62
Tensile strength, psi	Machine	1635	1510	1066	1790	3290	1625
	Transverse	1550	1440	870	1865	2720	1570
Elongation at break, %	Machine	520	420	20	500	700	415
	Transverse	500	400	240	475	650	470
Set at break, %	Machine	14	13	59	10	495	18
	Transverse	11	9	51	11	438	18
S-100, psi	Machine	350	350	-	300	950	335
	Transverse	320	350	630	375	920	280
S-200, psi	Machine	800	760	-	795	1060	750
	Transverse	740	760	845	915	1020	615
S-300, psi	Machine	1170	1120	-	1220	1230	1210
	Transverse	1110	1120	-	1370	1180	1020
Tear strength, ppi	Machine	206	181	303	196	429	201
	Transverse	111	181	276	195	417	221
Hardness, Duro A:							
Instant reading	-	62	57	73	55	84	59
10-sec. reading	-	58	54	70	52	81	54
Puncture resistance, lb	-	51.8	39.4	33.6	29.2	25.1	39.5
Elongation, in.	-	1.36	1.44	0.61	1.17	0.96	1.17
Specific gravity	-	1.173	1.122	1.199	1.160	0.938	1.176
Ash (dry basis), %	-	6.78	5.42	0.32	7.33	0.93	4.28
Volatiles, %	-	0.38	0.50	0.31	0.34	0.16	0.46
Exposure tests[e]	-	S,I	P,S,I	I	I	I	I

See footnotes at end of table.

APPENDIX A (Continued). PROPERTIES OF UNEXPOSED POLYMERIC MEMBRANES IN PROJECT

Item[a]	Direction of test	Neoprene			
Liner No.[b]	-	9	37	42[c]	90
Thickness, mils	-	60	73	19	37
Tensile strength, psi	Machine	2320	2400	17420	2185
	Transverse	2090	2330	9580	2010
Elongation at break, %	Machine	340	265	25	415
	Transverse	340	290	25	415
Set at break, %	Machine	11	2	2	26
	Transverse	13	3	2	25
S-100, psi	Machine	640	765	-	565
	Transverse	560	570	-	550
S-200, psi	Machine	1320	1800	-	1450
	Transverse	1150	1470	-	1225
S-300, psi	Machine	2060	-	-	1895
	Transverse	1830	2400	-	1700
Tear strength, ppi	Machine	220	221	1545	207
	Transverse	210	199	1802	196
Hardness, Duro A:					
Instant reading	-	71	69	74	68
10-sec. reading	-	66	67	73	61
Puncture resistance, lb	-	58.7	80.4	124.6	44.9
Elongation, in.	-	1.16	1.02	0.37	1.01
Specific gravity	-	1.500	1.451	1.302	1.388
Ash (dry basis), %	-	12.98	3.31	27.70	4.67
Volatiles, %	-	0.76	0.64	0.86	0.37
Exposure tests[e]	-	S,I	I	I	I

See footnotes at end of table.

APPENDIX A (Continued). PROPERTIES OF UNEXPOSED POLYMERIC MEMBRANES IN PROJECT

Item[a]	Direction of test	Polyvinyl chloride							
Liner No.[b]	-	11	17	19	40	59	67	88	89
Thickness, mils	-	30	20	22	33	33	22	20	11
Tensile strength, psi	Machine	2800	2640	2780	2935	2505	3020	3395	3715
	Transverse	2550	2520	2260	2640	2365	2765	2910	3085
Elongation at break, %	Machine	350	270	330	385	370	385	325	315
	Transverse	350	290	340	400	400	415	335	325
Set at break, %	Machine	90	68	97	62	45	192	102	196
	Transverse	103	77	105	71	60	207	101	205
S-100, psi	Machine	1355	1260	1150	1235	1020	1250	1870	1845
	Transverse	1205	1130	1060	1115	895	1110	1600	1530
S-200, psi	Machine	1980	2080	1890	1825	1570	1820	2610	2715
	Transverse	1740	1850	1590	1610	1355	1585	2190	2195
S-300, psi	Machine	2585	-	2620	2445	2160	2430	3230	3520
	Transverse	2255	-	2170	2150	1860	2135	2770	2880
Tear strength, ppi	Machine	374	353	295	350	306	340	463	408
	Transverse	370	317	275	316	287	297	470	391
Hardness, Duro A:									
Instant reading	-	85	81	80	81	80	81	85	87
10-sec. reading	-	79	76	72	74	71	75	80	82
Puncture resistance, lb	-	37.4	25.8	24.0	43.1	37.3	27.8	28.6	17.0
Elongation, in.	-	0.63	0.69	0.71	0.72	0.78	0.68	0.56	0.48
Specific gravity	-	1.275	1.264	1.231	1.289	1.280	1.245	1.255	1.308
Ash (dry basis), %	-	6.20	5.81	3.65	8.09	6.94	6.70	2.80	5.67
Volatiles, %	-	0.11	0.09	0.05	0.21	0.31	0.03	0.17	0.03
Exposure tests[e]	-	S,I,L, N	P,S, I,L	S,I	I	L,N	I	I	I

See footnotes at end of table.

APPENDIX A (Continued). PROPERTIES OF UNEXPOSED POLYMERIC MEMBRANES IN PROJECT

Item[a]	Direction of test	Polyethylene	PVC + pitch	Elasticized polyolefin	Polyester elastomer	Polybutylene
Liner No.[b]	-	21	52	36	75	98
Thickness, mils	-	11	80	23	7	8
Tensile strength, psi	Machine	1700	1185	2645	6770	5625
	Transverse	2590	1005	2540	6765	5580
Elongation at break, %	Machine	320	150	675	560	390
	Transverse	690	175	650	590	375
Set at break, %	Machine	177	36	460	340	346
	Transverse	667	18	430	370	331
S-100, psi	Machine	1270	1175	880	2715	2330
	Transverse	1030	860	865	2455	2360
S-200, psi	Machine	1470	-	975	2880	3035
	Transverse	1050	-	960	2585	3200
S-300, psi	Machine	1680	-	1145	3610	4405
	Transverse	1120	-	1150	3315	4610
Tear strength, ppi	Machine	415	292	388	911	355
	Transverse	360	208	369	782	380
Hardness, Duro A:						
Instant reading	-	97	75	90	93	94
10-sec. reading	-	97	69	87	93	93.7
Puncture resistance, lb	-	13.9	62.3	26.3	29.9	13.9
Elongation, in.	-	0.76	0.49	0.97	1.30	0.66
Specific gravity	-	0.931	1.294	0.938	1.236	0.915
Ash (dry basis), %	-	0.00	9.46	0.90	0.38	0.08
Volatiles, %	-	0.36	0.39	0.15	0.26	0.12
Exposure tests[e]	-	P,S,I, C,G	I	I,L,N	I,L,N	I,C

[a] Tests performed were tensile, elongation, modulus and set, ASTM D412; Duro A, ASTM D2240; tear strength, ASTM D624; puncture, FM 101B, No. 2065; specific gravity, ASTM D297; ash, ASTM D297; volatiles (weight loss in 2 h at 105°C).
[b] Contractor's liner number.
[c] Fabric-reinforced.
[d] Gained weight.
[e] C, leachate collection bags; G, used as liner of all generators; I, in immersion test; L, leachate osmosis bag; N, NaCl osmosis bag; P, primary test specimens; S, secondary test (specimens buried in sand).

APPENDIX B. PROPERTIES OF MEMBRANE LINER MATERIALS AFTER 8 MONTHS IN LEACHATE FROM SIMULATED MUNICIPAL SANITARY LANDFILLS.

Item[a]	Direction of test	Chlorinated polyethylene			Chlorosulfonated polyethylene		
Liner No.[b]	-	12	38	86	3[c]	6[c]	85
Thickness, mils	-	36.0	36.0	23.0	34.0	33.5	35.0
Leachate absorption, %	-	9.5	10.2	8.5	19.2	13.3	14.4
Increase in area, %	-	3.3	3.0	3.0	7.0	4.6	8.8
Volatiles, %	-	7.9	8.3	7.5	18.6	1.21	12.6
Tensile strength, psi	Machine	2190	1940	1850	1790	2190	1980
	Transverse	1660	1860	1740	1700	1920	1680
Elongation at break, %	Machine	340	340	480	580	230	250
	Transverse	460	480	380	620	240	320
Set at break, %	Machine	195	185	130	250	75	60
	Transverse	195	165	140	265	75	90
S-100, psi	Machine	1115	1170	760	365	940	875
	Transverse	480	455	320	250	775	485
S-200, psi	Machine	1525	1465	1080	500	1930	1690
	Transverse	735	680	500	290	1620	1030
S-300, psi	Machine	1960	1825	1460	665	-	-
	Transverse	1065	1025	800	375	-	1600
Tear strength, ppi	Machine	210	185	150	170	250	220
	Transverse	200	170	145	160	210	205
Hardness, Duro A:							
Instant reading	-	81	82	74	67	74	77
10-sec. reading	-	72	75	66	63	71	73
Puncture resistance, lb	-	50.7	50.1	27.1	38.5	48.7	54.5
Elongation, in.	-	1.00	0.99	1.06	1.86	0.76	0.96
Specific gravity, dried	-	1.354	1.335	1.389	1.393	1.325	1.294
Ash (dry basis), %	-	14.52	12.06	18.08	33.88	2.10	2.63

See footnotes at end of table.

APPENDIX B (Continued). PROPERTIES OF MEMBRANE LINER MATERIALS AFTER 8 MONTHS IN LEACHATE FROM SIMULATED MUNICIPAL SANITARY LANDFILLS.

Item[a]	Direction of test	Ethylene propylene rubber					Butyl rubber
Liner No.[b]	-	8	18	83[c]	91	41	44
Thickness, mils	-	66.0	50.0	36.0	36.0	19.5	67.5
Leachate absorption, %	-	6.0	8.4	2.8	20.9	0.5	1.8
Increase in area, %	-	3.6	4.8	1.2	13.5	-0.1	0.3
Volatiles, %	-	2.9	6.0	3.0	12.7	0.3	1.4
Tensile strength, psi	Machine	1700	1360	990	3410	3080	1470
	Transverse	1660	1460	920	2380	2480	1520
Elongation at break, %	Machine	480	350	240	460	700	440
	Transverse	510	380	330	360	640	490
Set at break, %	Machine	18	9	50	20	485	20
	Transverse	18	9	75	15	435	25
S-100, psi	Machine	415	385	930	730	940	295
	Transverse	355	360	665	330	930	240
S-200, psi	Machine	925	865	960	1750	1070	635
	Transverse	820	815	845	1355	1000	540
S-300, psi	Machine	1305	1235	-	2565	1225	1055
	Transverse	1200	1195	890	2085	1140	910
Tear strength, ppi	Machine	195	125	285	160	375	185
	Transverse	195	135	280	165	345	195
Hardness, Duro A:							
Instant reading	-	64	56	74	58	85	59
10-sec. reading	-	60	53	70	54	82	54
Puncture resistance, lb	-	55.1	43.1	27.8	27.5	25.2	37.9
Elongation, in.	-	1.26	1.18	0.51	1.12	0.84	1.13
Specific gravity, dried	-	1.168	1.113	1.194	1.110	0.935	1.172
Ash (dry basis), %	-	6.35	5.36	0.30	6.38	0.98	4.29

See footnotes at end of table.

APPENDIX B (Continued). PROPERTIES OF MEMBRANE LINER MATERIALS AFTER 8 MONTHS IN LEACHATE FROM SIMULATED MUNICIPAL SANITARY LANDFILLS

Item[a]	Direction of test	Neoprene			
Liner No.[b]	-	9	37	42[c]	90
Thickness, mils	-	70.5	72.5	20.5	37.5
Leachate absorption, %	-	19.3	1.2	13.2	7.1
Increase in area, %	-	14.4	0.4	0.8	4.5
Volatiles, %	-	9.0	2.1	13.3	7.2
Tensile strength, psi	Machine	1720	2380	13510	2130
	Transverse	1450	2340	2800	1890
Elongation at break, %	Machine	300	260	20	400
	Transverse	280	300	50	390
Set at break, %	Machine	9	3	1	25
	Transverse	8	4	5	25
S-100, psi	Machine	400	770	-	310
	Transverse	310	580	-	405
S-200, psi	Machine	1060	1765	-	1380
	Transverse	890	1500	-	1110
S-300, psi	Machine	1690	-	-	1890
	Transverse	1470	2335	-	1625
Tear strength, ppi	Machine	105	215	1245	170
	Transverse	95	220	1285	155
Hardness, Duro A:					
Instant reading	-	59	74	73	68
10-sec. reading	-	55	72	71	60
Puncture resistance, lb.	-	63.9	90.6	82.5	49.6
Elongation, in.	-	1.21	1.11	0.35	1.05
Specific gravity, dried	-	1.436	1.459	1.275	1.388
Ash (dry basis), %	-	10.58	5.33	26.31	4.51

See footnotes at end of table.

APPENDIX B (Continued). PROPERTIES OF MEMBRANE LINER MATERIALS AFTER 8 MONTHS IN LEACHATE FROM SIMULATED MUNICIPAL SANITARY LANDFILLS.

Item[a]	Direction of test	Polyvinyl chloride						
Liner No.[b]	-	11	17	19	40	67	88	89
Thickness, mils	-	31.0	21.5	21.5	32.5	22.0	20.0	11.0
Leachate absorption, %	-	2.9	2.3	1.6	1.2	1.6	1.0	2.5
Increase in area, %	-	2.4	1.9	1.9	1.4	0.4	0.5	1.1
Volatiles, %	-	2.4	2.3	0.9	1.4	1.4	2.4	2.3
Tensile strength, psi	Machine	2940	2560	2720	2670	2850	3220	3560
	Transverse	2700	2320	2490	2430	2660	2660	3160
Elongation at break, %	Machine	360	340	380	390	380	340	310
	Transverse	380	350	440	390	440	360	350
Set at break, %	Machine	95	60	80	65	85	90	90
	Transverse	100	65	105	75	110	100	110
S-100, psi	Machine	1330	1150	1145	1105	1125	1460	1710
	Transverse	1255	990	970	980	1010	1140	1455
S-200, psi	Machine	1915	1695	1680	1650	1685	2130	2570
	Transverse	1770	1440	1410	1470	1460	1665	2165
S-300, psi	Machine	2505	2335	2170	2200	2280	2840	3420
	Transverse	2345	2000	1865	1955	2000	2275	2870
Tear strength, ppi	Machine	360	300	290	315	285	345	340
	Transverse	350	305	265	275	285	330	320
Hardness, Duro A:								
Instant reading	-	85	79	77	82	80	84	87
10-sec. reading	-	80	74	72	75	74	79	83
Puncture resistance, lb	-	43.6	32.5	24.8	45.5	29.8	28.7	20.1
Elongation, in.	-	0.69	0.78	0.64	0.80	0.73	0.60	0.70
Specific gravity,dried	-	1.277	1.268	1.231	1.287	1.246	1.251	1.288
Ash (dry basis), %	-	6.45	5.39	3.64	6.63	5.39	2.81	5.59

See footnotes at end of table.

APPENDIX B (Continued). PROPERTIES OF MEMBRANE LINER MATERIALS AFTER 8 MONTHS IN LEACHATE FROM SIMULATED MUNICIPAL SANITARY LANDFILLS.

Item[a]	Direction of test	Poly-ethylene	PVC + pitch	Elasticized polyolefin	Polyester elastomer	Poly-butylene
Liner No.[b]	-	21	52	36	75	98
Thickness, mils	-	12.5	83.5	23.0	6.0	8
Leachate absorption, %	-	0.6	5.8	0.1	2.0	0.1
Increase in area, %	-	-0.2	4.0	0.6	1.3	0.4
Volatiles, %	-	0.0	6.1	0.4	1.4	-0.2
Tensile strength, psi	Machine	3090	1090	2480	6720	5420
	Transverse	2880	920	2180	7760	5500
Elongation at break, %	Machine	580	200	620	580	380
	Transverse	660	190	590	640	360
Set at break, %	Machine	455	40	430	360	230
	Transverse	520	15	385	345	210
S-100, psi	Machine	1370	990	940	2455	2395
	Transverse	1175	745	895	2665	2420
S-200, psi	Machine	1465	1090	1030	2745	3015
	Transverse	1220	930	975	2835	3305
S-300, psi	Machine	1685	-	1195	3010	4375
	Transverse	1255	-	1130	3665	4735
Tear strength, ppi	Machine	405	225	390	740	410
	Transverse	360	175	380	625	400
Hardness, Duro A:						
Instant reading	-	90	73	89	89	92
10-sec. reading	-	90	67	87	89	91
Puncture resistance, lb	-	15.9	53.6	28.5	19.6	20.2
Elongation, in.	-	0.99	0.51	1.02	1.11	0.74
Specific gravity, dried	-	0.928	1.290	0.938	1.232	0.904
Ash (dry basis), %		0.03	9.65	0.93	0.33	0.01

[a] Tests performed were tensile, elongation, modulus and set, ASTM D412; Duro A, ASTM D2240; tear strength, ASTM D624; puncture, FM 101B, No. 2065; specific gravity, ASTM D297; ash, ASTM D297; volatiles (loss to constant weight at room temperature, plus loss in weight in 2 h at 105°C).

[b] Contractor's liner number.

[c] Fabric reinforced.